THE ROLE OF LEARNING IN RESISTANCE TO CAPTURE BY PHYSICALLY SALIENT IRRELEVANT SINGLETONS

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Abstract

When observers search for a singleton shape, their attention can be captured, that is, they can be distracted, by an irrelevant singleton along the dimension of color. Attempts have been made to explain this phenomenon in terms of bottom-up guidance based on the physical properties of the display. The color singleton is more physically salient, that is, it stands out more in the display, than the target. However, when observers are forced to search for a particular shape, the typical finding is that they will not experience attentional capture by the irrelevant singleton. This had led to the argument that attentional guidance is top-down and based on current goals. In the first case participants were set to look for singletons, referred to as singleton detection, and therefore were distracted by the irrelevant color singleton, and in the second case they were searching for a particular shape, referred to as feature search, and therefore were not influenced by color. There is more recent evidence that past experience can also control attentional guidance. We found that past experience with the salient feature of the irrelevant color singleton is what allows participants to resist attentional capture, even when they have no past experience with target features. This resistance to capture appears transfer to trials where participants can use either a singleton detection strategy or a feature search strategy, but not trials where a singleton detection strategy is required. We also found that capture can occur when participants are forced to engage in feature search, but cannot learn to associate a particular color or colors with the irrelevant singleton. During singleton detection, past experience in terms of varying color singleton intensity can modulate the magnitude of capture. We believe that resistance to capture depends on experience with the salient feature of the distractor rather than factors that are

either purely bottom-up or purely top-down, although physical properties and search strategy do play a role.

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Chapter 1: Visual search and attentional capture

We experience a rich visual world that contains more information to be potentially extracted than could possibly reach higher visual areas, especially given that the information is constantly updated as our environment changes or we move through the environment. The ability to attend to particular items in the visual field instead of others allows us to fully process items that are important, rather than items that are not behaviorally relevant.

At the same time, we know that we often end up being aware of and influenced by items that are not relevant to our current goals. Subjectively we feel that we can usually ‘pay attention’ to things that are important, such as an important lecture, but sometimes find ourselves distracted by unwanted input such as a loud conversation in the hall. Most of us would like to avoid distraction as much as possible in daily life, and the present research explores the way past experience influences whether or not observers will be distracted by irrelevant items during visual search.

Before we can get into a discussion of distraction, we must first examine what attention is and how it operates. William James (1890/1998) famously said, “Everyone knows what attention is” (p. 403), yet one of the difficulties in discussing and researching attention is that the word ‘attention’ can refer to multiple processes, even when restricting the discussion to visual attention. It is difficult to pin down a precise, non-controversial definition. Still, most theories of visual attention involve processes of selection, some of which may be automatic and some of which may be effortful and under volitional control. James himself said, “It implies withdrawal from some things in order to deal effectively with others” (p.404) which suggests that there is a limit to the information that the mind can “deal effectively” with and that selectivity is a way of getting around this problem. Several of the most influential general theories of visual attention will be discussed briefly.

Feature-integration theory (FIT)

One of the most important theories of attention is the feature-integration theory, or FIT (Triesman & Gelade, 1980). This theory was meant to explain certain visual search findings, especially the fact that search for a separable feature, such as a blue item among red and green or an ‘S’ among ‘T’s and ‘X’s, was much easier than search for a conjunction such as a green ‘T’ among brown ‘T’s and green ‘X’s. Search for a separable feature was faster, and also unaffected by the number of distractors (at least on target-present trials), while the time it took to find a conjunction of features increased as the number of distractors increased.

According to FIT, there is an early, parallel stage of processing. During this stage, it is possible to detect and identify features. Texture segregation and figure-ground groupings based on features will occur during this stage. It requires another step for features to be located and if attention is diverted or overloaded, illusory conjunctions can occur. That is, if there is a green ‘A’ next to a purple ‘B’, an observer may report seeing a purple ‘A’ if they did not fully attend to the objects.

Focal attention is the next stage of processing, and is required when searching for conjunctions, which must be spatially localized to be identified. Attention must be directed serially to the location of each relevant item. Under FIT visual attention operates like a zoom lens (or a spotlight—one of the most popular metaphors for how visual attention works). Attention can be distributed over a group of items that share a relevant feature, but it must be focused onto a particular object in order for the observer to process that object as an object. An object has features that are integrated. The observer knows that the item in that location is a green ‘A’, not just that there is some green in that location and some lines of particular orientations in that location. By attending to an object, the observer can identify it.

Items that are found easily are ones that can be detected during the parallel stage of processing. The addition of more items to the display will not slow search. Other types of items must be searched for serially. According to FIT, targets that require serial search are not only those defined by conjunctions, but those that are defined by the lack of a feature rather than the presence of a feature, such as an ‘O’ among ‘Q’s (Treisman & Souther, 1985). This is how search asymmetries, where searching for item X among item Y is much easier than searching for item Y among item X, can arise. The main distinction in types of search under FIT is between serial and parallel, although search rates can be affected by factors such as how qualitatively different the target and distractors are along the dimensions that define them.

The theory of visual attention (TVA) and the neural theory of visual attention (NTVA)

The theory of visual attention is another general attentional theory (Bundesen, 1990). Like FIT, TVA involves two basic stages of processing, unselective and selective, which essentially correspond to parallel and serial. The basic assumptions of TVA are that the objects that are perceived are the ones that enter visual short-term memory (VSTM), which has a strict capacity limit of only a few items. The reason that some items enter VSTM and some do not can be explained by two mechanisms: filtering and pigeonholing.

Filtering is the mechanism by which targets are selected instead of distractors. If a certain perceptual category, such as green, is *pertinent* (important for behavior), then items are given more attentional weight in proportion to the amount of sensory evidence that the items belong in that category. Items with more weight are more likely to be selected. The neural theory of visual attention (Bundesen, Habekost, & Kyllingsbæk, 2005) proposes that filtering is implemented by increasing the number of neurons that represent behaviorally important objects, an idea partly inspired by Moran and Desimone (1985). Under NTVA, it is assumed that neurons represent a specific feature and respond to only one item that falls within their receptive field. The probability that a neuron will represent a given object that falls inside its receptive field (RF) is equal to the attentional weight of object divided by sum of all attentional weights of all objects in that neuron's RF.

Pigeonholing refers to the process of making perceptual categorizations in a way that is needed for whatever behavior is relevant, for example, determining whether an item is green or not. This means that there is a bias toward categorizing items as belonging to the relevant category, and therefore items that belong to that category are categorized more rapidly than other items. According to NTVA, this involves a multiplicative scaling of the level of activation in neurons that code for the pertinent feature.

Filtering and pigeonholing can be easy to confuse. An example of filtering would be giving increased attentional weight to items in proportion to their 'greenness.' An example of pigeonholing would be an increased likelihood that items are categorized as being green. In NTVA terms, if green is a pertinent feature, neurons are more likely than usual to represent green objects and sensory information that provides evidence of green neurons will lead to a higher level of activity in neurons that represent green than would otherwise occur. Filtering and pigeonholing work to increase the rate of processing for items that have target characteristics, which means that those items are more likely to 'win' one of the limited spaces in VSTM. Categorizations get lost if VSTM is full, so perception is a winner-takes-all process under TVA.

Under NTVA the unselective wave of processing is when the weights are computed and stored in a saliency map. A saliency map is really an interconnected set of maps of different locations at different scales, perhaps located in the pulvinar. The weights are how much a neuron in the map is activated in terms of spikes/sec. The weights control the remapping receptive fields so that more neurons are responding to high saliency objects. Activity is sustained in such neurons through a VSTM feedback mechanism, and all types of categorization of the important object will be sped up. This is how you 'pay attention' to an object under NTVA.

The term focused attention deals with the ability to focus on targets instead of distractors and is particularly relevant to the present research. TVA describes two types of search when looking for a target among distractors: one-view search and many-view search. With one-view search, the target pops out and can be found without eye movements or shifts of attention. For this to be possible, there must be a high degree of target-distractor discriminability. The visibility of the target against the background and whether non-targets can be perceptually grouped will also determine whether one-view search can take place.

Many-view search is needed for conjunction search, but also if target distractor discriminability is low or if the target is simply difficult to see against the background. Some search asymmetries can be explained when one item type has high visibility and one item type has low visibility (e.g. dark gray and light gray against a white background). In the most extreme case of many-view search, each item is processed with its own reallocation of attention, although reallocation is not always necessary. TVA represents a move away from thinking of attention as a mental searchlight, although there is still the idea that attention is reallocated from item to item in order to perform some types of visual search.

The biased-competition model

The biased-competition model (Desimone & Duncan, 1995) is somewhat similar to TVA in that it is based around the idea of limited capacity, competition between objects for representation, and the ability to selectively filter, but it lacks the distinction between filtering and pigeonholing (see Bundesen, Habekost, & Kyllingsbæk, 2005). Under the biased-competition model there is limited processing capacity at several points between sensory input and behavior. Objects are processed as wholes, so objects must be competing for limited resources. Competition is biased by bottom-up factors and also in a top-down way toward information that is relevant to behavior. This bias can come from basic features of the stimulus such as color and location as well as complex conjunctions of features. Observers searching for a particular target have an attentional template, which is essentially a description of the visual information needed to find the target, and that template can control the bias.

Even when only two objects are presented, behavior shows evidence of competition. When attention is divided, performance is usually worse. The limitations on performance arise mostly at the level of sensory input, and not from competition when it comes to memory or making responses. The performance decrement is independent of eye movements and largely independent of spatial separation.

According to the biased-competition model, there are over 30 cortical visual areas where objects compete for processing, as part of both the ventral and dorsal processing streams that originate in area V1, the primary visual cortex. As information moves further along these streams the complexity of processing increases and the neurons have larger receptive fields. The RFs are a processing resource and with a larger RF it is more likely that there will be multiple objects competing for a response from that neuron, which will only respond to one object.

Unlike in FIT, the construction of object representations occurs in parallel before attentional selection. Under this model, individual neurons are not assumed to only represent one feature, but can represent a complex conjunction of features (Desimone, Schein, Moran, & Ungerleider, 1984), so feature binding is considered a less important problem under the biased-competition model. The most dramatic difference between the biased-competition model and FIT is that in the biased-competition model attention is an emergent property that results from the way neural mechanism resolve completion for processing, and ultimately the control of behavior. It is nothing like a moving spotlight that is rapidly reoriented toward different items in a display.

Guided Search 4.0

The last influential theory of visual attention that will be discussed before moving specifically into discussing attentional guidance and attentional capture is Guided Search 4.0 or GS4 (Wolfe, 2007). According to GS4, there is an early parallel stage of processing and a later stage of object recognition that also occurs in parallel, during which objects are matched with stored representations. It is the bottleneck between these two stages that limits performance when an observer is looking for a target item among distractors and GS4 is largely a model of how that bottleneck works. Under GS4, there is no distinction between parallel and serial search because all visual search is considered to require a combination of parallel and serial processes.

When the term attention is used in GS4 it is referring to control of what is selected during the bottleneck in processing. Search is guided by the outputs of channels for features such as orientation and color. The different channels are not for separate feature dimensions or for specific feature values, but for categories. For instance, the current model has four orientation channels: horizontal, vertical, right-tilted and left-tilted. The channels for the red-green axis of color are the categories of red, yellow and green. This is a simplification used for the sake of convenience and the actual channels involved in perception are likely somewhat different, especially since color is a three-dimensional feature space.

The greater the difference between the response in a certain channel to a particular item and the response in that channel to the rest of the display, the greater the bottom-up salience of that item. The weighted sum of bottom-up activation and top-down activation for each item in the display, along with some noise, is what forms an activation map, somewhat similar to the saliency map in TVA. The activation map guides attention. Higher weights can be put on the output of one channel than on the others within that dimension, which is how top-down guidance influences selection. Under this model only some attributes from early vision can guide attention, and color happens to be particularly effective.

When search is guided to an item (i.e. selectively attended), it is classified as either a target or a distractor through a diffusion process, where evidence accumulates over time until it crosses either a target threshold or a distractor threshold. The parameters of accrual rate and the value of the threshold affect how the model behaves. Diffusers have a limited capacity, which is why a bottleneck occurs at this point. Both selective and non-selective processing are then subjected to a final bottleneck that can be considered attentional in nature before the output of processing leads to a behavioral decision (and possibly conscious awareness).

What is attentional capture?

Although there is clearly an ongoing debate over the nature of visual attention, in the following discussion it will be assumed that selective attention involves prioritizing particular features or locations in a way that leads to certain items being selected for greater processing, and which ultimately enables observers to make a behavioral response relating to a target item. The issue under examination in the present work is attentional control of feature-based attention, specifically the extent to which initial prioritization and initial selection depends on the physical salience of the item, explicit top-down goals, and selection history.

It is not reasonable to suggest that attention is never influenced by our goals or never influenced by the physical properties of items in our visual field, but there is an important debate over when those factors come into play, to what degree, how much automaticity is involved, and so on. One way to examine the initial guidance of attention is to consider cases of attentional capture. The present work is concerned with instances where attention is captured, that is, directed to a non-target item that is irrelevant to behavioral goals. Another way to word this, in order to get away from the 'attention as spotlight' metaphor, is that a non-target item is selected and represented in a way that leads to reduced task performance.

Certain items can capture attention due to properties that give them a high degree of salience, such as sudden onset and looming, at least in the sense that search is faster for a target that has that property (Yantis & Jonides, 1984; Franconeri & Simons, 2003). In general, this makes clear evolutionary sense--we would want to become aware of things like obstacles, predators, or prey animals. However, there is reason to think that attentional capture by non-target items can be a different story (Yantis & Jonides, 1990; Yantis & Egeth, 1999), in that non-target items with features such as a sudden onset do not always capture attention unless they share a feature with the target, especially if they fall outside the spatial location to which an observer is strongly attending.

The type of attention I refer to in the following, unless otherwise stated, is covert attention, that is, attention without eye movements. Because the lack of eye movements makes the direction of covert attention difficult to pinpoint, in is generally inferred. For instance, if response time to a target stimulus takes longer when a salient distractor is present, this can indicate that the observer first attended to and then disengaged from the distractor before attending to the target. Distractor-present response time minus distractor-absent response time can provide a measurement of the amount of capture.

Attentional capture can also be assessed behaviorally through response accuracy, since if the display offsets while participants are still attending to the distractor they will be less accurate than if they had initially attended to the target. Target/distractor compatibility effects are also worth examining, since if participants are attending to the distractor they are likely to be slower and/or less accurate when a feature of the target requires a different response than does that aspect of the distractor. For instance, a person might have to respond one way to even numbers and another to odd. If the target contains an even number, a distractor containing an odd number would be incompatible, and, if attended, might lead to an inaccurate or slow response compared to trials in which the distractor contained an even number. A compatibility effect is a strong indication that a slower or less accurate response was due to capture and not to non-spatially selective filtering slowing down processing as a whole, which is a possibility in attentional capture paradigms (for example, see Becker, 2007).

Another way that attentional capture is detected and measured is the use of evoked response potentials (ERP). There are several components of the ERP waveform that might be of interest. The N2pc is a marker of selective attention, which has been used in a variety of attentional capture studies (e.g. Hickey, van Zoest, & Theeuwes, 2010) as it can indicate whether observers are attending to the to the target or the distractor and provide insight into the timecourse of attention. Attentional capture can also be examined by comparing P1/N1 response to a probe presented after at the array. A person with a low P1/N1 response to a probe at the target location and a high response to a probe at the distractor location must have experienced attentional capture (because a high response is expected in response to a probe located at the position the observer was already attending). A person who overcame attentional capture would be expected to have a high P1/N1response to a probe at the target location and a low response to a probe at the distractor location. This method allows researchers to calculate the amount of capture a participant experienced (Fukuda & Vogel, 2009).

It is also possible to observe overt attentional capture, also know as oculomotor capture. This is when observers direct an eye movement, called a saccade, to a distractor instead of the target. For instance, participants instructed to make a saccade to a unique shape with an unpredictable identity will experience oculomotor capture by a task-irrelevant salient distractor. Interestingly, they experience covert attentional capture but not oculomotor capture by the salient distractor when they know what shape the target will be (Theeuwes, de Vries, & Godijn, 2003). Oculomotor capture is more likely when participants are instructed that the probability of a distractor on that trial is low, and less likely when participants believe the distractor has a high probability of appearing (Moher, Abrams, Egeth, Yantis, & Stuphorn, 2011).

How does attentional capture relate to theories of attention?

Feature-integration theory does not make specific predictions about attentional capture, but it does focus on the existence of efficient 'pop-out' search for separable features, which is the basis of the additional singleton paradigm that will be described in the following section. The idea of a parallel stage of processing followed by a focal stage informs many discussions of visual perception and the influence of the idea of attention like a zoom lens can be seen in the attentional window hypothesis and rapid-disengagement theory discussed later. The parallel stage of processing works well to explain attentional guidance to salient singletons.

The theory of visual attention can easily explain attentional capture by an item that shares a ‘perceptual category’ with the target. The pertinence, or task-relevance, of items determines the weight given to the item, and that interacts with sensory evidence. All items that share the feature (or in some cases conjunction of features) being selected for are more likely to be selected, but because VSTM is limited, there is a chance that distractors similar to the target will be selected instead of the target. TVA does less well to explain capture by items with non-pertinent features, but it does include a wave of unselective processing from which a saliency map is computed. In the absence of strong top-down weighting, only sensory signals would be left to guide attention.

Under biased-competition, the bias can come from both bottom-up and top-down sources. With this view, it is easy to explain capture by irrelevant items if their bottom-up salience is enough to ‘win’ against the top-down weighting of another item that results from an attentional template. Attentional capture would be especially likely if there was a degree of uncertainty in the attentional template. Under this model, whether a target or distractor is selected is simply a matter of the strongest source of bias.

Guided search does a good job of explaining attentional capture by irrelevant items because GS4 does not allow for completely top-down guidance. There is both bottom-up activation and top-down activation, and the weight that gets put on bottom-up activation can never be set to 0, which means that search is always partially guided by physical salience. With a strong enough bottom-up signal there is always the possibility that attentional capture will occur. GS4 can also explain top-down attentional capture. For example, let's say that the search is for a red 'X.' In this case red will be heavily weighted. The resulting activation map will guide attention to the area of the display that has the most red in contrast with the background. Attention might initially be guided to a red 'O' if it has a more visible red than the 'X' (perhaps the red 'O' appears on top of a patch of green and the red 'X' appears on a patch of orange) or if the target item is absent from the display that that moment in time.

Attentional guidance and the additional singleton paradigm (ASP)

As used during the preceding discussion of theories of attention, the word *salience* refers to the quality of being noticeable or important. An item in the visual field is physically salient when a certain feature is concentrated in that location in a way that is in contrast to neighboring areas. This is also referred to as bottom-up salience. An item can also have top-down importance that does not depend on its physical characteristics so much as its task relevance. For instance, your coat among a variety of coats my not be very physically salient, but it will be important to you both because of your familiarity with it and your goal of finding it so that you can put it on and go outside. These types of items are sometimes said to have top-down salience, although Bacon and Egeth (1994), following Bundesen (1990), used the term *pertinence*, for when an item's importance was derived from task demands in order to make the difference clear.

As discussed earlier, items with high physical salience tend to 'pop-out' when part of a visual display. Search for such items appears to be parallel, that is, the entire display can be analyzed at once without the need for spatially selective attention (though spatially selective attention might be necessary to fully process the salient item). If the target is the item that pops out, search will be very efficient, meaning that it will be just as quickly detected in the presence of few distractors as in the presence of many distractors (Triesman & Gelade, 1980). Determining the speed of detection for various numbers of items will yield the search slope. If with four items the search takes 100 ms and with eight items the search takes 200 ms, the search slope is 25 ms per item (because it takes 100 ms longer to search for four more items). The closer the search slope is to zero, the more efficient it is, with parallel searches having a near-zero slope.

In cases where a search display is being analyzed in parallel, where in the display will selective attention first be directed? Theeuwes (1991) found that when observers searched for a pop-out singleton target along a particular dimension, response times were slower in the presence of a salient singleton along another dimension. That is, pop-out singletons along the irrelevant dimension captured their attention. It did not appear that the initial guidance of attention could be controlled by top-down selection of a particular dimension. A follow-up experiment by Theeuwes (1992) found a lack of top-down selectivity even with practice.

The paradigm employed by Theeuwes is generally referred to as the additional singleton paradigm and is the basis of the present research. Displays in Experiment 1 of the 1992 study consisted of 5, 7 or 9 outline shapes spaced evenly around an imaginary circle surrounding a fixation point. The shapes each contained a line segment, and the task was to report the orientation of the line segment inside a particular item, a task that is assumed to necessitate focal attention. In Experiment 1, the target was a green circle among green diamonds—a shape singleton. These displays could contain a red diamond—the additional singleton, this time along an irrelevant dimension, which gives the paradigm its name. Examples of search displays with an with and without an additional singleton are shown in Figure 1. I will use the term *singleton color* to refer to the color of the irrelevant singleton and *majority color* to refer to the target and the other non-target items.

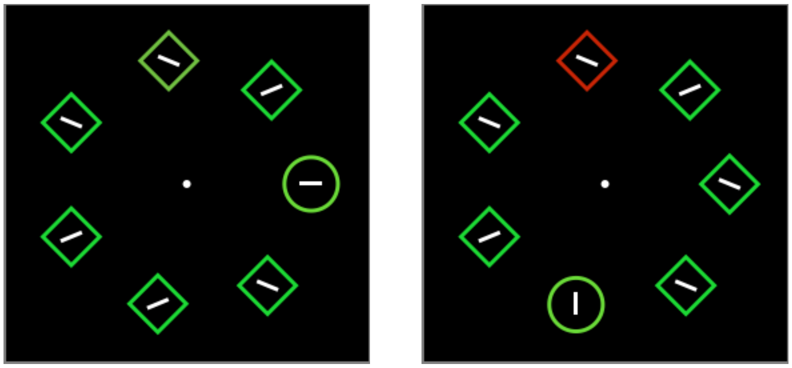

Figure 1. Examples of additional singleton displays adapted from Theeuwes (1992). The target is the circle in both cases. The red diamond in the display on the right is an irrelevant, yet physically salient, singleton.

Response times were slower when the color singleton was present, demonstrating that observers experienced attentional capture by the irrelevant singleton. The same study also looked at the effect of a shape distractor during the search for a color singleton and found that the shape distractor captured attention as long as the colors were difficult to discriminate, that is, the color singleton was less salient than the shape singleton. Many variations of this task are used throughout the attentional capture literature, but the basic principle is the same.

At one end of the theoretical spectrum is the idea that initial guidance of attention is always due to bottom-up factors, which was Theeuwes's own explanation of these results. Under any bottom-up theory of attentional capture, the determining factor in whether a distractor captures attention is how physically different it is from its surrounding. For example, a red color singleton among green items will capture attention during a shape search for a circle, but a diamond among circles will not capture attention during a color search for a green item among red items. This is not because participants were able to select for color in the second case, but because the shape difference was less salient than the color difference. When the experiment was repeated with yellowish green and yellowish red instead of an easily distinguishable green and red, the color singleton did not capture attention during the shape search task, but the shape distractor did capture attention during the color search task. Once again, the most salient singleton captured attention in each case (Theeuwes, 1992).

Bottom-up theories usually do take some amount of selection history into effect, particularly with regards to inter-trial priming (e.g. Pinto, Olivers, & Theeuwes, 2005), but the most important characteristic of the irrelevant singleton in determining whether it will capture attention is its physical salience. A red item among green captures attention, but so should a green item among red, or a blue item among red as long as the exact shades are sufficiently different, and so on. Top-down selectivity is impossible, which means that one cannot guide the initial deployment of attention using knowledge of the upcoming target's feature value or feature dimension.

The spatial cuing contingent capture paradigm

The additional singleton paradigm is, of course, only one paradigm used to study attentional capture. There were studies that took place around the same time as Theeuwes's initial studies, which came to essentially the opposite conclusion—the initial orientation of attention depends on an observer's top-down attentional control settings (Folk, Remington, & Johnston, 1992). In this initial study, using a paradigm referred to as spatial cuing contingent capture, the search array consisted of four outer boxes and one center box. In the onset target condition one of the outer boxes had either an 'X' or an '=' and participants had to indicate the identity of the target. In the color target condition all outer boxes had either an 'X' or an '=' inside and the target was the red one. The center box was always left empty.

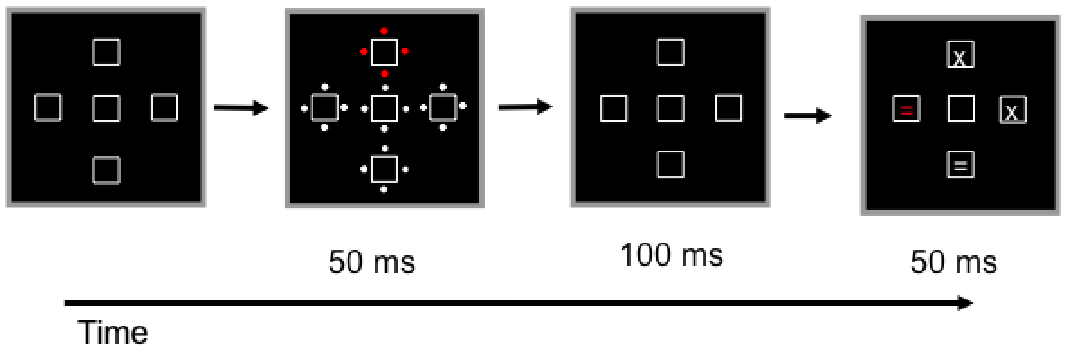

Figure 2. A spatial cuing contingent capture trial similar to that used by Folk, Remington, & Johnston (1992). The task is to indicate the identity of the red target. The trial sequence is a placeholder display, then a cue display, then another placeholder display, and finally a search display. In this particular case the cue is the same color as the target, but appears in an invalid location. Both the cue and the target are color singletons.

In Experiment 1, the search array was preceded by a cue display where one of the boxes was surrounded by four white dots, serving as an onset distractor. The effect of the onset distractor was assessed by comparing valid trials, where the cue appeared at the same location as the upcoming target, with invalid locations, where the cue appeared at a different location as the upcoming target. In this particular experiment, the different cue conditions were presented in separate blocks. Because this was a validity design, capture was considered to have occurred when response times to on invalid trials were significantly longer than on valid trials, which is what happened when the target was an onset target, but not when the target was a color target.

In Experiment 2, where the cue display consisted of circles around all five boxes, with the circles around only one box colored red rather than white, the red color singleton cue captured attention when the target was a red color singleton (as in Figure 2), but not when the target was an onset target (that is, when it was the only character present in the display). The same results were obtained in Experiment 3 when the cue conditions were not blocked such that the cue was equally likely to appear in any of the outer four boxes.

In Experiment 4, the procedure was the same as Experiment 2, but with green circles used for the cue display. The green cue captured attention in this case, even though the target was red, which Folk et al. interpreted to show that while there was selectivity at the level of orienting to different types of feature discontinuities, selectivity might not possible at the level of specific feature values. The fact that 'static discontinuities,' that is, salient color singletons, not just onset distractors, could capture attention was similar to what Theeuwes had demonstrated. However, the selectivity found by Folk et al. was completely different. In these experiments, the color singleton target only captured attention when the target was a color singleton and the onset distractor only captured attention when the target was an onset target. It was clear that further work would have to be done to reconcile these results.

The theory of distinct search modes

An attempt to explain the apparently dichotomous findings of Theeuwes (1992) and Folk et al. (1992) led to the creation of search mode theory. Bacon and Egeth (1994) replicated the findings of Theeuwes but disagreed that top-down selectivity was impossible. They argued that participants in the Theeuwes studies were employing top-down attention in order to detect singletons in general. Attentional capture resulted from a failure to be selective for singletons along a particular feature dimension, not a failure of all top-down selectivity. They created a modified version of the paradigm in which participants still searched for a circle, but now with one, two, or three unique forms in each display (see Figure 3), so that a singleton detection strategy would not lead participants directly to the target.

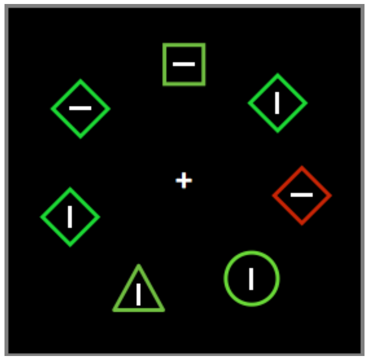

Figure 3. Example of a search display with several unique forms, also referred to as a feature search display, adapted from Bacon and Egeth (1994). The target is the circle. This is a color singleton distractor present trial.

With these more heterogeneous displays, participants no longer experienced capture, and even on trials where the target was the only shape singleton, capture by the color singleton did not occur as long as such trials were mixed into blocks containing heterogeneous displays. Participants also did not experience capture by the irrelevant singleton when there were multiple targets. The authors argued that in the former case participants were in ‘singleton detection mode’ and were open to distraction by any singleton. In the latter, participants were in ‘feature search mode,’ set to look for a specific shape, and were not susceptible by capture by any type of singleton. Search mode theory argues that participants *can* use feature search mode when the identity of the target is known, but participants aren’t necessarily going to as long as other search strategies are available.

Bacon and Egeth argued that search modes could be used to explain the results of Folk et al. (1992) if participants in Experiment 4 were in singleton search mode, even though feature value information about the target was available to them, it would explain why the green singleton captured their attention. Because the target was a singleton, there was no reason why they couldn’t have been in singleton detection mode.

What search mode theory doesn’t really speak to is the difference between onset stimuli and stimuli that are singletons along a certain feature dimension (are onset stimuli not treated by the system as singletons, despite how different they are from their surroundings?), and whether search modes beyond singleton detection and feature search exist. Bacon and Egeth predicted that if the target in a spatial cuing task were a non-singleton (for instance, a red item in a heterogeneously colored display), participants would be forced to use feature search mode and the green singleton cue would no longer capture attention. One of the important implications of Bacon and Egeth is that if experimenters want to be sure of the search strategy that their participants are using, they must try to make it the only search strategy viable for finding the target.

Something to keep in mind about Bacon and Egeth (1994) is that the search slopes were not completely flat in the conditions where capture was not obtained. The search slopes were mostly under 10 ms per item and at most 11.5 ms per item, which is less than what would be expected from a strictly serial search. However, since the search slope was not completely flat the search slope in the feature search version of additional singleton can be used to argue that the lack of capture is due to non-parallel search.

Attentional capture continued to be explored with the additional singleton paradigm and contingent capture paradigms, including spatial cuing contingent capture. Folk and Remington (1998) tested the hypothesis that observers would become selective for color when forced into feature search mode. One group of participants searched for a specific color target that was also a shape singleton, while the other group searched for a specific color target that was not a singleton. Figure 4 shows an example of what a spatial cuing experiment with a non-singleton color target might look like. A cue validity effect was indeed found for same-color cues when participants searched for a non-singleton target, such that participants were less accurate on trials with same-color cues in a different location from the upcoming target than in the same location,

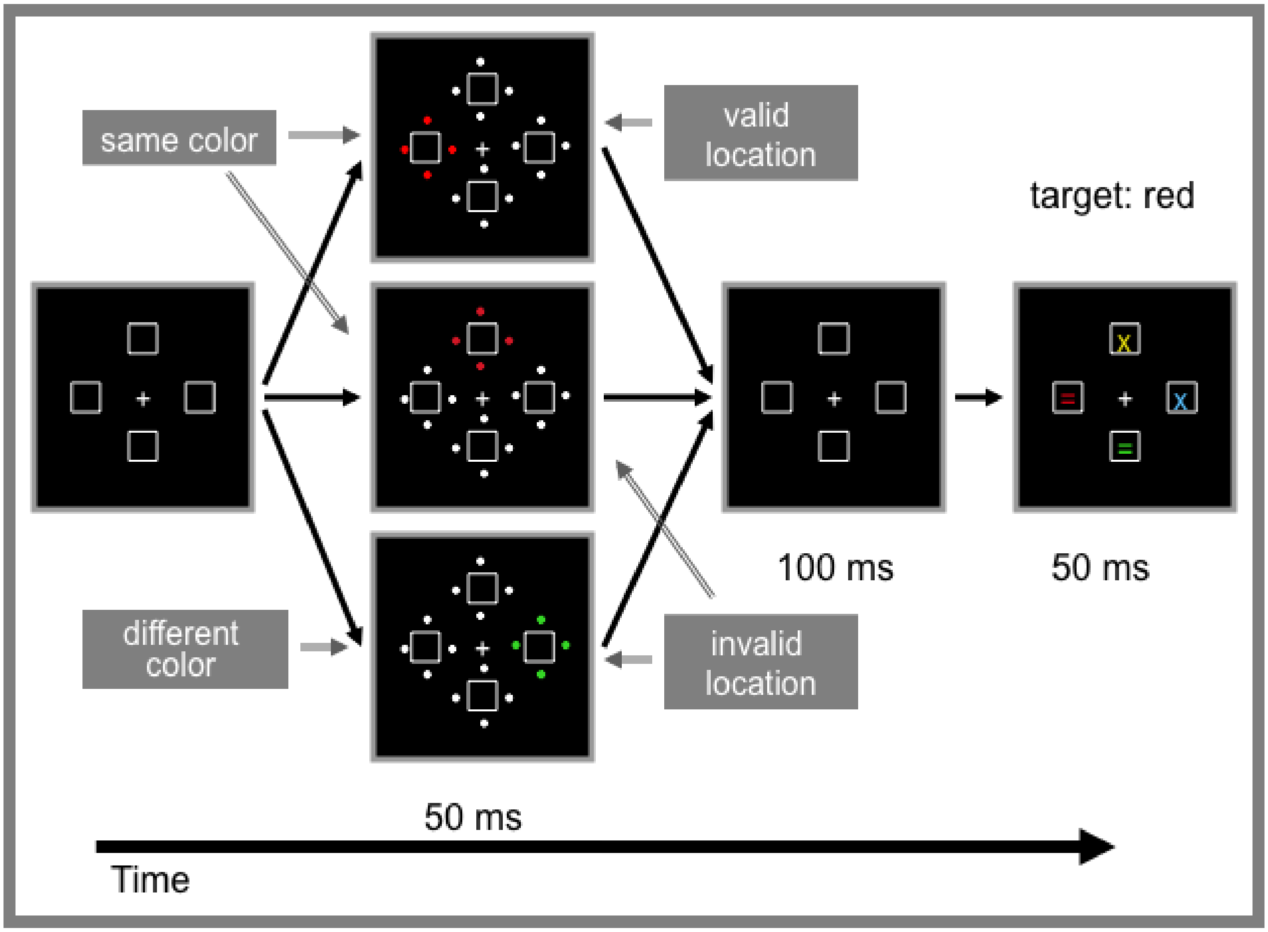

Figure 4. An example of the spatial cuing contingent capture paradigm with a non-singleton target. The task is to search for the red item and indicate which character it is. The trial sequence begins with a placeholder display, then a non-informative cue display. Three possible cue displays are shown, two that are the same color as the target and one that is a different color than the target. The location of the cue dots could be valid, that is, the same as the target, or invalid. The cue display was followed by another placeholder and then the actual search display.

presumably because their attention was drawn to the location of the cue. For example, a participant searching for the red target as in Figure 4 would take longer to identify the target after seeing the middle cue display than the top cue display. There was no cue validity effect with different-color cues. Whether the green cue display in Figure 4 was in a valid or invalid location would not have affected performance. Somewhat more surprisingly, the same results were obtained in the singleton target condition, where the target might have been a red character among gray ones, and the authors raised the possibility that some aspect of the experiment that was different from Folk et al. (1992) might have biased participants into using feature search mode even when it was not necessary.

One of the questions that arose about attentional capture was whether capture would still occur if participants knew what location to pay spatial attention to, unlike in the additional

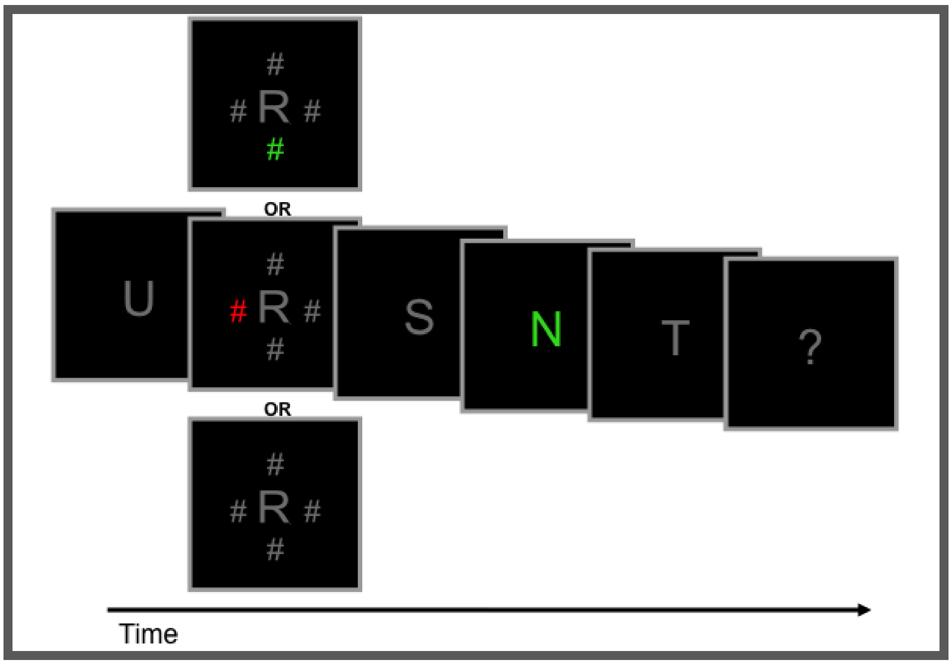

Figure 5. An RSVP contingent capture trial. The target is the green letter. Three examples of distractor displays are given: same-color, different-color, and all gray.

singleton paradigm, where the target location is unpredictable. In RSVP contingent capture (Folk, Leber, & Egeth, 2002) observers must report a target letter that appears in a rapidly presented stream of letters. Two trials before the target letter, there is a distractor display with the current letter surrounded by four hash marks. (Distractor displays are often used at lag -1, 0, and 1 for comparison, but it was at lag 2 that the greatest effect was observed.) Capture is said to have occurred if participants are less accurate at recalling the target when the distractor display was present then when it was absent.

In Experiment 1 of Folk et al., the target was a predictable color singleton letter in a stream of homogenously colored letters (e.g. the target was a green letter in a stream of gray letters), as shown in Figure 5. In this case, a distractor display with a single colored hash mark among gray hash marks captured attention, in terms of leading to lower accuracy in identifying the target letter, no matter what color it had. A distractor display consisting of 4 gray letters, included to rule out non-spatial filtering costs as an explanation for performance decrements, led to similar performance as the no distractor condition.

In Experiment 2, a consistent color target (e.g. green) was again used, but now was embedded in a heterogeneously colored stream of letters, in order to force participants to adopt a feature search strategy. With this manipulation, the distractor display containing a same-color hash mark led to reduced accuracy as compared to the other conditions. In this particular case, the different-color distractor display and 4 gray distractor display led to similar accuracy, which was slightly lower than accuracy in the absence of a distractor display, which might indicate some degree of non-spatial filtering.

Taken together, the results indicated that a color singleton distractor outside the focus of spatial attention could capture attention. The influence of the color singleton differed based on how the target was defined, with participants not experiencing capture from different-color distractors when forced to use feature search, though the still experienced capture by an item with the target-defining feature.

Can the attentional window hypothesis explain these results?

Theeuwes argued that there were alternative explanations for the lack of capture in Bacon and Egeth, particularly the attentional window hypothesis (Theeuwes, 2004). He saw search mode theory as too circular of an argument, since lack of capture is used as evidence that participants are in feature search mode, but the search mode is at the same time the explanation for those results. According to Theeuwes, the reason that the color singleton did not capture attention on Bacon and Egeth (1994) type feature search displays could have been due to the addition of more unique shapes leading to both the target and the distractor decreasing in salience. A less salient target could also have explained Bacon and Egeth's finding of slightly less efficient search for a non-singleton target than a shape singleton target. If uniqueness in general, not along a particular dimension, leads to attentional capture, then adding more heterogeneity of any kind could reduce the salience of individual items overall. If the target was not salient enough, then participants could not be performing a parallel search in order to find it.

Theeuwes (2004) used displays similar to the Bacon and Egeth displays with three unique shapes, but increased the overall number of items to 12 or 20 in order to make both the unique shapes (which included the target) and the color singleton distractor more salient. Using this design the search slope was flat, indicating completely parallel search, and the color singleton did capture attention. The attentional window is the area in which features compete in parallel and the one with highest physical salience becomes the initial focal point for selective attention. The size of the attentional window is what is under top-down control. For a pop-out search it might be the size of the entire visual field, but for a feature search for a target among heterogeneous distractors it will be the size of only one or two items. This means that search will have to be at least partially serial and capture will not occur because the distractor will often, by chance, fall outside the attentional window. The attentional window is parsimonious in that the same mechanism would explain both singleton detection and feature search results.

This theory was based in part on findings by Yantis and Jonides (1990) that abrupt onsets do not capture attention as long as they fall outside an area where attention is strongly focused and his own work showing that abrupt onsets captured attention when participants did not know in which of the four possible locations the target would occur, but did not capture attention when participants were cued with 100% validity about where the target would appear (Theeuwes, 1991). Under the attentional window theory, the area that is strongly attended (and in which capture by any items can occur) is affected by more than spatial uncertainty, since both the

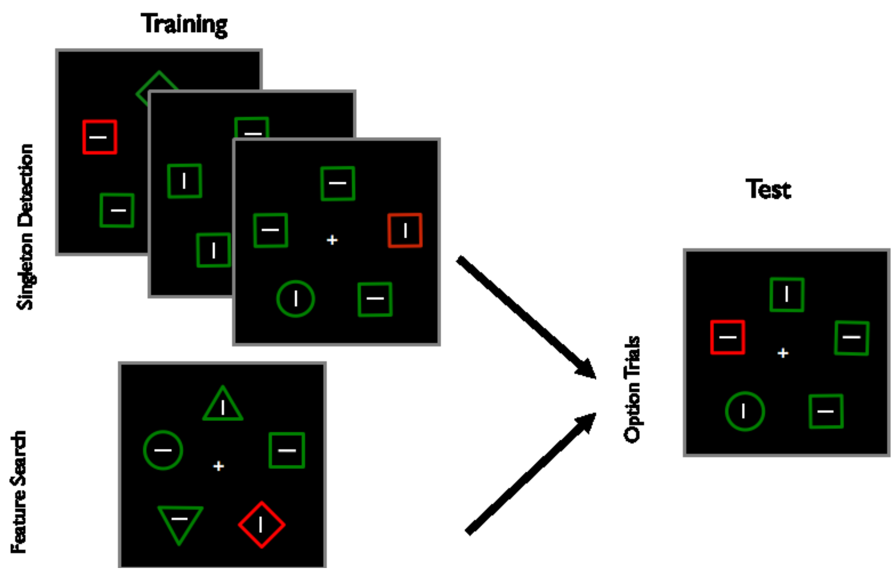

Figure 6. An overview of the additional singleton transfer paradigm used by Leber and Egeth (2006b). The two groups of participants received different training, but the same type of trials at test. The target was an unpredictable singleton during singleton detection training, a circle during feature search training, and a circle at test.

singleton target and non-singleton target versions of the additional singleton paradigm have the same levels of target uncertainty. The size of the attentional window is under top-down control, but top-down attention cannot be selective for dimensions or affect orienting within the attentional window—the initial orienting of focal attention is due to bottom-up factors.

In response, Leber and Egeth (2006b) argued that the search slopes in both the condition of Bacon and Egeth (1994) where most of the trials had unique shapes besides the target and

Theeuwes's (2004) replication of those results were quite shallow, especially on those trials where the target was a singleton and where capture did not occur (about 5 ms/item). It did not seem like search was at all serial on these trials, yet there was a difference in capture based on participants apparent search strategies. As for the experiment where the display size was greatly increased, Leber and Egeth argued that the changes actually created four salient pop-out items (the target, the other two unique shapes, and the color singleton), which might have caused participants to adopt a singleton detection strategy and therefore be susceptible to capture by the irrelevant singleton.

Leber and Egeth (2006b) were able to demonstrate resistance to capture occurring with the same displays used by Theeuwes (1991, 1992) where search slopes were parallel and capture had previously been obtained. They did so using a transfer paradigm in which groups of participants were given different kinds of initial training, but the same types of test trials. The training trials for one group consisted of singleton detection trials, which were similar to the typical additional singleton displays used previously, but in which the target singleton could be one of either a circle, diamond, or triangle among non-target squares, in order to ensure that participants could only find the target through a singleton detection strategy and not through a feature search strategy. The other group received feature search displays as in Bacon and Egeth (2004) as the training.

The test displays were like the typical Theeuwes (1991,1992) additional singleton paradigm displays in that the target was always a singleton circle among diamonds. They referred to these as option trials, since participants could find the target either through singleton detection (since the target was a shape singleton) or feature search (since the target was know to be a circle), although the previous findings of attentional capture with these displays pointed to singleton detection as the default search mode used for option trials. They found that participants who received singleton detection training experienced capture on the test trials, while those who received feature search training did not. They concluded that search modes could transfer from training to test and that the attentional window hypothesis could not account for these results because the test displays were physically equivalent for both groups (and there was not difference in search efficiency between groups in the test phase).

Similar results were also obtained by Leber and Egeth using RSVP contingent capture (2006a). Half the participants received singleton detection training where a distractor display at lag 2 led to low accuracy in discriminating the target if one of the hash marks was a color singleton of either the same or different color than the color singleton target. All gray hash marks led to similar performance as the absence of a distractor display. In the feature search condition, where the target was a specific color within a heterogeneous RSVP stream, only the distractor display with a color singleton that matched the target color produced a marked performance decrement.

At test, with option trials where the target was a known color singleton, the pattern of distractor interference transferred from the training, with only the same color distractor display causing interference after feature search training, and both the different and same color displays causing interference after singleton training. Results from RSVP contingent capture are somewhat even harder to explain with the attentional window hypothesis than results from the additional singleton paradigm since an ideal observer in RSVP contingent capture should always have an attentional window narrow enough to exclude the distractors, though it is certainly possible that observers widen or narrow their attentional windows in a non-ideal way during different versions of the task.

Can the absence of capture effects be explained by rapid disengagement?

One of the major debates in the attentional capture literature focuses on when top-down factors come into play and can lead to reduced or undetectable capture by salient items. According to the disengagement hypothesis (Theeuwes, 2010), initial visual selection is always bottom-up, and the most salient item is the item to which attention is directed. Later, once recurrent feedback comes into play, that is, once initial processing of the display has taken place in higher visual areas and the result is sent back to lower visual areas, selection is biased by top-down factors such as expectancy and goals. This means that observers cannot resist capture by a highly salient distractor, but they stop processing it and move on faster if they know that the item lacks target features.

The disengagement hypothesis is used to explain results from the spatial cuing contingent capture paradigm, where the distractors appear before the search array. If the amount of time that it takes to disengage from the distractor when a salient cue does not match the target features is less than the stimulus onset asynchrony (SOA) between the cue display and the search display (typically 150 ms), then the amount of capture would appear to be nil even if the salient item actually did capture attention. In cases where significant capture is seen it is because the cue possesses target features and observers process items containing relevant features in more depth. Additionally, under the disengagement hypothesis, the shift to cues that match the target are endogenous (top-down) rather than resulting from true exogenous (bottom-up) capture as it would be if the cue was a salient singleton that did not match the target.

Note that rapid disengagement is not used to explain results from additional singleton feature search. Theeuwes's explanation for those findings is the attentional window hypothesis discussed previously. Under Theeuwes's view, the only way that top-down control affects the initial feedforward sweep of processing is through adjusting the size of the attentional window. However, rapid disengagement might be able to explain differences in how strongly a distractor captures attention in this paradigm. If the distractor does not match the target, disengagement is fast, but if it is similar to the target, disengagement will be slow. This could explain why the magnitude of capture is generally greater in cases where the target shape is unpredictable, since the color singleton cannot be rejected as the target on the basis of shape alone, and must be rejected on the basis of comparing it to nearby items (i.e. realizing that it is not a shape singleton) or on the basis of color, which might not be efficient in cases where the target is not defined by color. If the target shape was predictably a circle, participants who were captured by the distractor could quickly reject any non-circular item.

On the other side of this debate, those supporting the contingent capture model argue that rapid disengagement does not provide a good explanation for the results of spatial cuing studies and may not actually be falsifiable (Folk & Remington, 2010). It has been shown that when the target color is know in advance of a trial, a blue cue will only produce a cuing effect if the target is blue. When the target is unpredictably either red or green, the blue cue produces a cuing effect just like the red and green cues (Folk & Anderson, 2010). This result cannot be explained by rapid disengagement, but makes sense if participants had a top-down set to look for singletons in general and therefore experienced capture by the blue singleton. In addition, there is no evidence of an effect of a salient non-matching cue even when the stimulus onset asynchrony (SOA) between the cue and the target is only 35 ms (Chen & Mordkoff, 2007), which is such a short interval that it is highly unlikely participants could have re-oriented attention during that time if attention had initially been directed to the distractor. The fact the argument for rapid disengagement relies on arguing that there are cuing effects that are too rapid to detect makes it difficult to disprove depending on just how rapid the effects are argued to be. It is unclear what the lower limit is presumed to be for a capture effect by a non-matching item.

There is also evidence from outside the attentional capture literature that feature-based attention begins to operate even in advance of stimulus presentation, and that it can be used to filter out distractors, not just to enhance processing of targets. Using ERP, Zhang and Luck (2009) found that when observers had to detect the dimming of dots of certain color that overlapped with dots of another color, task-irrelevant probe dots appearing in the opposite hemifield evoked a larger P1 wave when in the target color than when in the distractor color. This indicated that feature-based attention could influence the feedforward sweep of processing that occurs within 100 ms of stimulus onset. An experiment that included a neutral baseline color, which only appeared on the task-irrelevant side of the display, found that the difference in P1 amplitude resulted from inhibition of the distractor color rather than enhancement of the target color (Moher, Lakshmanan, Egeth & Ewen, 2014).

How might taking selection history into account better explain attentional capture?

Theories of attentional capture involving stimulus-driven attentional guidance, the attentional window, and rapid disengagement from distractors seem directly opposed to search mode theory, contingent capture, and filtering of distractors. However, a third possible determinant of attentional control exists in addition to bottom-up and top-down guidance—selection history (Awh, Belopolsky, & Theeuwes, 2012). Selection history encompasses various phenomena such as priming, perceptual learning, and value-driven attentional capture that result from factors outside the physical stimuli on a given trial but at the same time are different than explicit goals and search strategies. Whether these are all considered top-down is partly a matter of semantics, since it has been argued that observers do not have particularly good insight into their own search strategies and ability to ignore distraction (Kawahara, 2010), but it does seem theoretically useful to distinguish between influences that result purely from an observers goal state combined with current task demands and those that do not and will, at least in some circumstances, work against the observer's current goals.

In terms of attentional capture, it is now a well-known phenomenon that features previously associated with reward will capture attention during a search task where that feature is no longer rewarded (Anderson & Yantis, 2013; Anderson, Laurent, & Yantis, 2011). In the value-driven attentional capture paradigm, there is a training phase during which participants search for a color-defined target. Participants are given a high monetary reward after correct responses to targets of one color and a lower monetary reward after correct responses to targets of another color. During the test phase, participants search for a unique shape such as a diamond among circles, which is similar to the additional singleton paradigm. However, in this paradigm each shape is a different color, so there is no color singleton. If one of the non-targets is in a previously rewarded color, it will capture attention as if it gained salience through having been previously rewarded. This does not happen if participants merely searched for those colors without receiving rewards in the training phase, so it is not simply an effect of previously attended/selected items receiving priority. The magnitude of capture is also modulated by the level of reward, such that the highly-rewarded color more strongly captures attention, which is further evidence that learned associations between reward and color are driving attentional capture.

The present research is particularly concerned with the ability to resist capture by irrelevant distractors. There are recent findings that shed light on the importance of past experience on attentional capture, even in the absence of reward. These findings provide evidence against both the idea that top-down selectivity is impossible in the initial stages of visual processing, and the idea that that search mode theory as originally envisioned serves a full explanation for the resistance to capture seen in feature search.

To start with, resistance to capture does not occur immediately during a feature search. During the first 24 trials of a feature search, and during the first 24 trials after the singleton color is changed, attentional capture can be detected (Vatterott & Vecera, 2012). If only search mode, and not learning, mattered we would expect resistance to capture to be immediate. If only bottom-up factors mattered, we would not expect a difference between initial trials and later trials.

Furthermore, the transfer of resistance to capture from feature search training to option test trials will also only occur under specific conditions. Transfer will not occur if there is no distractor present during feature search training, or when the color of the singleton at test is different than the color of the singleton used during training (Zehetleitner, Goschy & Müller, 2012). In both cases participants experienced a similar magnitude of capture at test, regardless of the training type. This indicates that a lack of experience with a distractor, and specifically the salient feature of that distractor, might lead to a lack of attentional control. If it was feature-search mode that was transferring, then the identity of the color singleton distractor, and probably even the presence of any color singleton distractor, should not have mattered.

There is also evidence for the importance of memory and some type of associative learning. Resistance to capture can be tied to a particular background context (Cosman & Vecera, 2013a).

This was a within-subjects experiment where one type of background was paired with feature search training and one with singleton detection training. At test, some option trials were paired with one type of background and some with the other. Participants experienced less capture on the option trials that were paired with the background associated with feature search training.

There is also evidence of the importance of learning in the ability to transfer resistance to capture from on type of trial to another that comes from a patient study (Cosman & Vecera, 2013b). A group of amnesiac patients with bilateral MTL damage and matched controls were given feature training followed after a brief delay of about 5 min by option test trials, as in Leber and Egeth (2006b). Both groups were able to resist capture during training. At test, the controls continued to resist capture, but the amnesiac patients experienced a substantial capture effect of 131 ms.

Goals of the current study

There are clear issues with search mode theory as it currently stands, but a purely stimulus-driven account of attentional capture does not provide a good explanation of the cases where resistance to capture is found. The present research aims to demonstrate that the experience an observer has with a salient but irrelevant distractor is crucial to explaining why the observer does or does not experience attentional capture.

The first goal of this study, presented in Chapter 2, is to demonstrate the key role of experience with the salient feature of the distractor in the transfer of resistance to capture. This will be done using a version of the additional singleton paradigm transfer paradigm based on Leber & Egeth (2006b) where target features can change from training to test. The intent is to show that experience with the distractor is sufficient to allow transfer and that experience with the features of the target itself is not necessary. This would demonstrate that attentional capture by a physically salient item can continue to be avoided even with changes to the top-down attentional set for the target.

The second goal, presented in Chapter 3, is to test the extent to which search strategy matters for resisting capture once that resistance has developed. This will be done by using a version of the additional singleton paradigm transfer paradigm where there is feature search training, but rather than allowing for the possibility of either search strategy at test, participants will be forced to use a singleton detection strategy. This will show whether or not learned resistance to capture can allow resistance to capture under conditions where attentional capture has previously always been found. If so, this would indicate that experience can influence attentional guidance even when search strategy is constrained.

The third goal, presented in Chapter 4, is to test the predictions of search mode theory against the predictions of an experience-based account specifically on behavior during feature search. Participants will be given feature search trials where the majority color and singleton color can swap values from trial to trial. In this case, it is predicted that they will experience capture because the swapping will completely disrupt any learning about the singleton feature. Majority and singleton color will also be switched between two colors in isolation to show that the inability to resist capture occurs as a result of swapping colors, and not just from any change in color.

The fourth goal is to explore the influence of past experience during singleton search, which will be presented in Chapter 5. This study will involve with an irrelevant singleton either increases, decreases, or remains constant in color intensity over the course of the experiment. At some points during the experiment, the color singleton should be less physically salient than the shape singleton target. Examining the magnitude of capture over both time and salience level will give us insight into conditions that lead to either enhanced or reduced levels of capture under circumstances where capture is expected to occur and explore the differing contributions of physical intensity, practice effects, and past distractor experience.

In sum, this research will underline the importance of past experience on attentional guidance during feature search, and point to specific areas where current bottom-up and top-down theories of attentional capture are lacking explanatory power. It will also provide more information about the specific ways that selection history can impact behavioral performance and introduce modifications to the additional singleton paradigm that will allow further study of past experience and learning. It will also shed new light on the strengths and weaknesses of various theories of attention and models of visual search.

Chapter 2: Resistance to capture by a specific feature is what transfers in additional singleton paradigm transfer studies

As discussed in Chapter 1, search mode theory (Bacon & Egeth, 2004) proposes the existence of two distinct search modes: singleton detection mode, where observers have a top down set for singletons but are unselective for type of singleton; and feature search mode where observers find the target based on a specific feature value or perhaps conjunction of features. In transfer studies such as those undertaken by Leber & Egeth (2006a, 2006b), where different patterns of capture occur on identical test trials based on the type of training, it is assumed that the search mode has transferred from training to test. The participants still in singleton detection mode are captured by the irrelevant singleton at test and participants still in feature search mode are able to resist capture.

However, it is hard to use search mode theory to explain the findings from more recent studies of transfer. Using a similar paradigm to the Leber and Egeth additional singleton paradigm transfer study (2006b), but leaving out the color singleton distractor during training results in all participants experiencing capture at test, even those that had experienced feature search training (Zehetleitner, Goschy, & Müller, 2012). If transfer occurred because participants who are forced to use a particular search strategy will persist with that strategy for as long as it is viable, and using feature search mode results in resistance to capture, then there should have been a transfer effect in this case.

For the sake of argument, let us say that the sudden introduction of a distractor in the test phase was so surprising that it could have caused participants to be jolted out of their previous search mode and default to singleton detection mode. In that case, we would expect that if participants were expecting the presence of distractors, transfer effect would occur. However, merely changing the color of the distractor appears to be enough to prevent transfer. In a different experiment of Zehetleitner et al. (2012), the color singleton was orange during the training phase and pink during the test phase (Figure 7). Feature search participants did not experience attentional capture by the orange color singleton during the training trials, but did experience capture by the pink singleton during the option trials of the test phase—i.e., there was a lack of transfer.

This experiment of Zehetleitner et al. (2012) also indicates that attentional window size is not what transfers in transfer studies. The attentional window hypothesis (Theeuwes, 2004), can easily explain cases where no capture occurs during feature search training, but does occur during the more homogenous test trials. It can even explain the original Leber and Egeth studies if it is assumed that attentional window size transfers, as is argued by Theeuwes (2010). Under the attentional window hypothesis, capture fails to occur during feature search because a spatially narrower attentional window is used for feature search trials than for singleton detection. The salient color singleton might fall outside of the attentional window, and therefore fail to capture attention. Narrowing the attentional window also slows down search, because the more attentional shifts are required to process the display, and according to this argument, the overall slowness of RTs could conceal small capture effects. It is possible for the attentional window to transfer from training to test, because the size of the attentional window is under top-down control, and this would explain the lack of capture on option trials following feature search training.

However, the same argument in favor of the attentional window hypothesis cannot be made based on the findings of Zehetleitner et al. (2012), where changing the color of the singleton led to capture regardless of training. The attentional window explanation of transfer would logically predict that attentional window size and slow search would transfer in the that study as well, leading to a lack of capture in the feature trained group. The color of the color singleton should be irrelevant. In actuality, feature training did not lead to a lack of capture on the test trials when singleton color was changed.

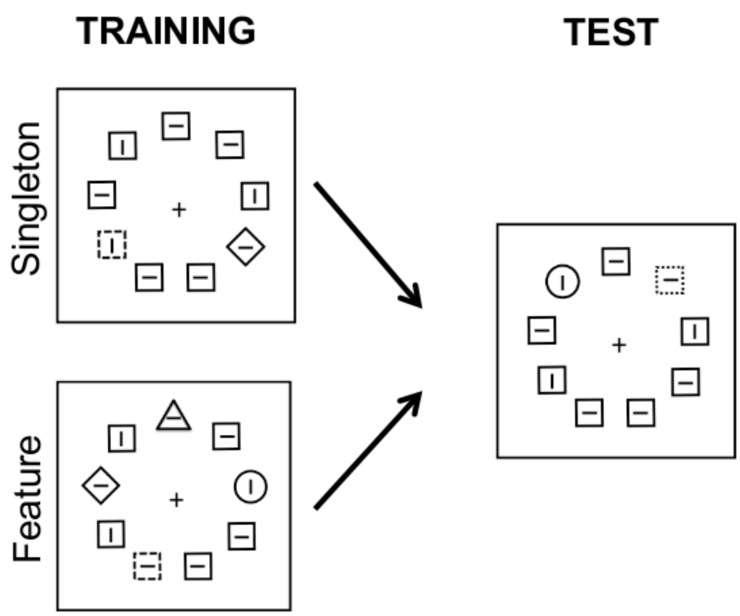

Figure 7. Example of color singleton present trials from Experiment 4 of Zehetleitner, Goschy, & Müller, 2012. The color singleton was always orange, here indicated by a dashed line, when it appeared during training and always pink, here indicated by a dotted line, when it appeared during test. Solid lines represent green.

Another experiment from that study showed that there is some distractor interference during feature-search training trials, but this disappears by the time participants are in the test phase (in a case where the color singleton is not changed from training to test) indicating that resistance to capture is not an immediate consequence of being in feature search mode. This is exactly what

Vatterott and Vecera (2012) also claimed. Combined, these findings seem to indicate that when transfer does occur, it is because participants are learning to ignore a specific distracting feature over time.

If having a top-down attentional set containing a specific target feature is not sufficient for overriding attentional capture, then it might not be necessary either. In order to provide support for the hypothesis that resistance to capture depends on experience with the salient feature of the potentially distracting item, and not on experience with the target features, the current study aims to demonstrate that the consistency of the distractor singleton color from training to test is sufficient for transfer to occur within the additional singleton paradigm, but a consistent target feature is not necessary. Features such as the target shape, non-target shapes, and color of the non-color singleton items were varied between training and test to rule out the possibility that participants were learning to better attend the relevant target shape or were learning to search only items that shared the color of the target.

In the following experiments we used the additional singleton paradigm with eight-item displays; the target feature was defined in terms of stimulus shape. On some trials all of the items were the same color. On other trials there were seven same-colored items and one differently colored item; by way of terminology we refer to these as the majority color and the singleton color, respectively.

Experiment 1

In Experiment 1, the majority color and the singleton color were both kept the same for training and test, but the set of shapes used in training was different from the one used in test. Thus, the specific feature that feature search participants were set to search for in training was different from the one they searched for at test (see Figure 8 for examples of singleton training trials, 8B for feature training trials, and 8C for test trials). If transfer did not occur, this would be consistent with resistance to capture only transferring when the same relevant stimulus feature is used during training and test. If transfer did occur it would suggest that transfer was tied to the color of the stimuli, despite the fact that the search task was related to shape only.

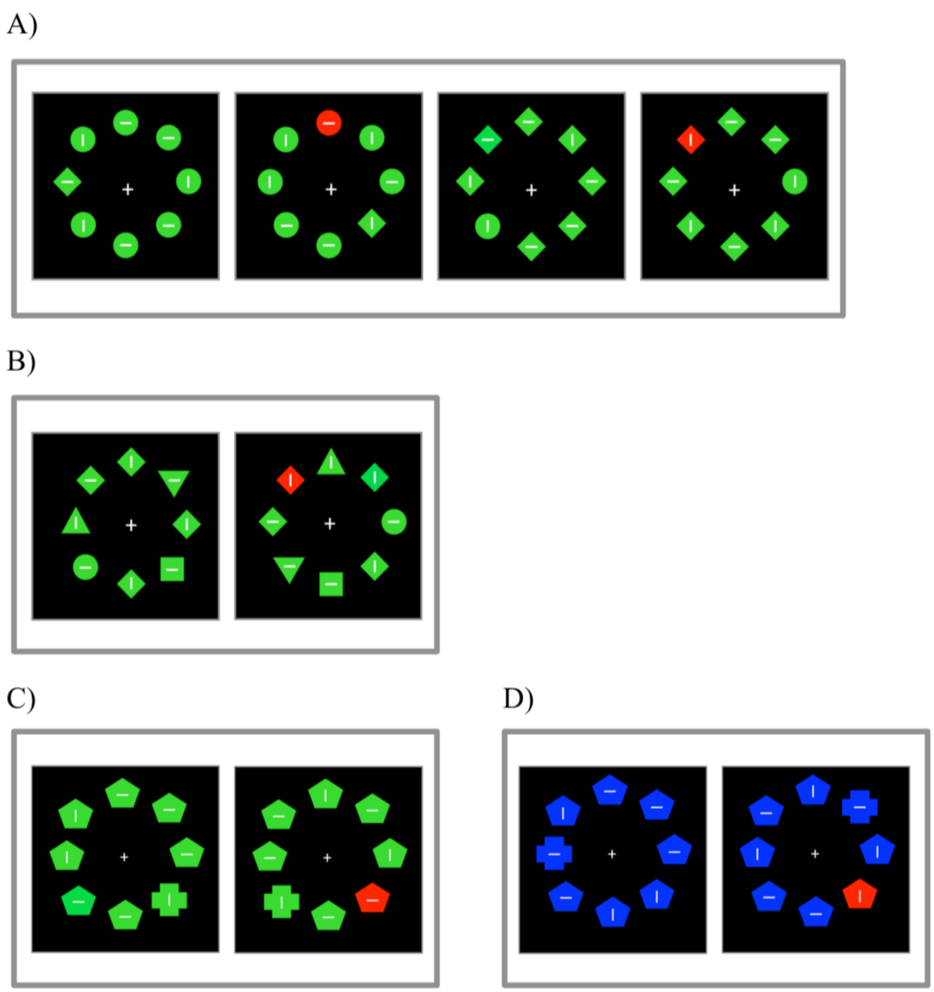

Figure 8. A) Four examples of singleton detection training trials where the majority color was green. The target was the uniquely shaped item, either a diamond or circle. A color singleton distractor was present on half the trials. B) Feature search training trials. The target was a circle on all trials. C) Option trials with and without distractors from the test phase in Experiment 1, where the target was a cross among pentagons, the majority color was the same as during training, and the color of the color singleton was the same as during training. D) Option trials from the test phase of Experiment 2, where the target was the cross, there was a different majority color than during training, and the color singleton was the same as during training.

Method

Participants

16 people (11 female) with an average age of 22.8 years participated in return for $10 compensation. All participants were at least 18 years of age and reported normal or corrected-to-normal visual acuity as well as normal color vision.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1280x1024 resolution and a screen refresh rate of 60 Hz, which was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background.

Stimuli and Procedures

Training. Each trial began with a fixation cross that appeared for 1000 ms, after which eight gray placeholder boxes slightly larger than the following shapes appeared for 500 ms. These were replaced by the actual stimuli, which remained onscreen until the subject made a response or 3000 ms had passed. On half the trials, a randomly chosen nontarget shape was a color singleton. These trials were considered the distractor-present trials, while those with all shapes the same color were distractor-absent trials. For half the participants, the target and nontarget were green (RGB value = [0 255 0]) and the singleton distractor was red (RGB value = [255 0 0]), while for the other half the target nontarget were blue (RGB value = [0 0 255]) and the singleton distractor was yellow (RGB value = [255 255 0]).

Stimuli were eight solid shapes arranged along an imaginary circle, 4.45˚ from the central fixation cross to the center of each shape. Inside each shape was a white line that could be either horizontal or vertical. Half the participants received the singleton search version of training where the shapes were either circles with a 2.22˚ diameter or equilateral diamonds 2.39˚ across. Seven shapes were the same and served as the nontargets. The unique shape was the target. Target and nontarget shape, target and nontarget location, and the orientation (horizontal or vertical) of each of the lines were all determined randomly for every trial, with equal probability. Singleton-detection participants were told to search for the item with the unique shape and that color was irrelevant to the task.

The feature-search version, which half the participants received, was very similar to the singleton-detection version, but the target was always a circle. In addition, the non-targets were always a square, a triangle pointing up, a triangle pointing down, and four diamonds, so that the target was not the only unique shape. The square was the same size as the diamond, just rotated, and the triangles were equilateral with an altitude roughly the same as the diameter of the circle. If a red color singleton was present in the display it was always one of the diamonds. Feature-search participants were told to search for the item with the unique shape and that color was irrelevant to the task.

The task was to report the orientation of the line inside the target shape by pressing either the right or the left mouse key as quickly and accurately as possible. Both response time and accuracy were recorded, with incorrect and no-response trials dropped from the analysis of response times. Participants were given 20 practice trials followed by 320 experimental trials, and were allowed a break between blocks of trials. Feedback was given in the form of a beep that played after incorrect or time-out trials.

Test. The test trials were very similar to the singleton detection training trials, but they were option trials—that is, the target was consistently a cross among pentagons. Participants were instructed to find the unique shape, which was a cross. Again, a color-singleton distractor appeared with 50% probability. Color did not change from training to test. For example, a subject who had green as the majority color and red as the singleton color during training had that same color assignment during test. Participants had 20 practice trials with feedback and 320 experimental trials. Subjects received feedback in the form of a beep that played after incorrect and time-out trials.

Results and Discussion

Trials with no response or an incorrect response were excluded from analysis. The training data were used to confirm that the search mode manipulation was effective (see Table 1 for the means). A mixed-model ANOVA revealed a significant main effect of type of search, $F(1,14)= 55.73$, $p < .001$, such that participants were faster in the feature search condition, a common finding (e.g., Leber & Egeth, 2006a) There was also a main effect of distractor, $F(1,14) = 20.77$, $p < .001$, such that subjects were overall slower in the presence of a distractor. More importantly, there was a significant interaction between training search mode and distractor, $F(1,14) = 16.23$, $p = .001$. Overall, reaction times in the feature-search condition were about 100 ms faster than in Leber and Egeth (2006a), while the reaction times were about 100-200 ms slower in the singleton detection condition, perhaps due to the fact that the target and non-target shapes switched in the current experiment, rather than having only the target change shape.

Color Singleton	Absent	Error Rate (%)	Present	Error Rate (%)
Training				
Feature	620(112)	4.0	631(98)	4.3
Singleton	1061(139)	7.3	1234(208)	10.2
Test				
Feature	683(138)	3.6	685(135)	4.1
Singleton	804(114)	6.8	841(143)	3.6

Table 1. Mean color singleton present and absent reaction times and standard deviations in milliseconds, as well as error rates, for Experiment 1 training and test phases.

The interaction between training mode and distractor presence reflects the fact that reaction times in the presence and absence of a salient distractor were nearly identical in the feature search condition (i.e., near-zero capture), but the distractor slowed responses in the singleton condition. The amount of capture is found by subtracting the average response time on distractor absent trials from the average response time on distractor present times. During training, the amount of capture for the singleton-detection group was 173 ms which was significant, $t(7) = 4.371$, $p = .003$. The existence of capture by the color singleton was expected for singleton-detection trials. In contrast, the feature-search group averaged an 11 ms difference between color singleton absent and present trials which was not statistically different from zero, $t(7) = 1.406$, $p = .202$, indicating that capture did not occur. This is what one would expect during search for a specific feature. Overall, this demonstrated that subjects had the pattern of distractor interference we expected given prior research on search under similar conditions (e.g. Leber & Egeth, 2006b).

For the test trials, a mixed-model ANOVA revealed a significant main effect of distractor, $F(1,14) = 7.62$, $p = .015$, and a marginal effect of type of training, $F(1,28) = 4.40$, $p = 0.054$. The key finding of this experiment was a significant interaction between training and the presence of the distractor, $F(1,28) = 6.293$, $p = .025$, which indicates that training did affect the magnitude of attentional capture during the test phase. Based on prior studies, we did not expect different results from using the green/red color set or the blue/yellow color set, so we did not include this factor in our analysis. In comparison to Leber and Egeth (2006a), reaction times here were a bit slower during test, especially in the singleton-trained condition, where participants were around 175-200 ms slower than in that previous study.

In the option trials of the test phase, (see Figure 9), participants trained in singleton detection experienced 38 ms of capture on average, which was significantly different from zero, $t(7) = 2.715$, $p = .030$. The feature-search trained participants experienced a 2 ms difference on average, which was not a significant amount of capture, $t(7) = .519$, $p = .619$. This means that even though all participants saw the same displays at test, the tendency to experience capture and/or the ability to resist capture by the color singleton must have transferred from the training trials to the test trials. The amount of capture was overall less in the singleton detection condition during test than it was in training. The reduced capture might indicate that feature-search mode and singleton-detection mode can operate at the same time, that is, participants are set to detect singletons and therefore experience capture, but also know the specific feature of the target and are able to use top-down control to some extent (Lamy, Carmel, Egeth & Leber, 2006).

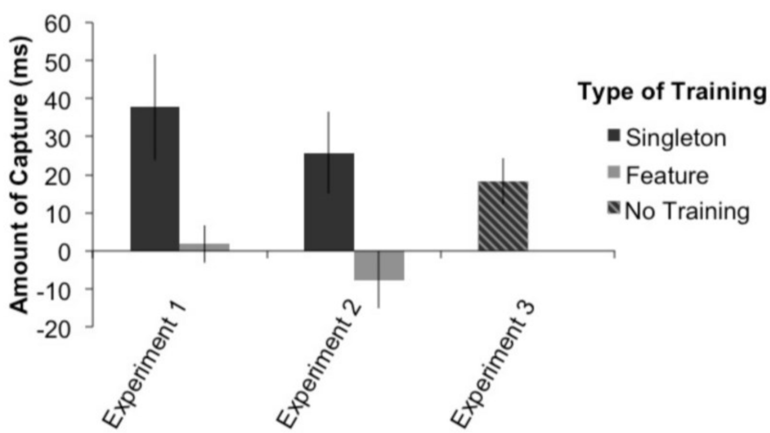

Figure 9. Amount of capture (color singleton present RT – color singleton absent RT) for option trials. In Experiment 1 and Experiment 2, there were two groups of participants who had received either singleton detection training or feature search training. The difference between the two groups indicates the presence of transfer. In Experiment 3, participants received option trials without any training.

As seen in Table 1, the error rates could not be used to explain the difference between color-singleton present and color-singleton absent trials in terms of a speed-accuracy tradeoff. If anything, participants made slightly more errors under conditions that led to slower response times.

Experiment 2

One concern with concluding that the results from Experiment 1 were due experience with resisting the singleton distractor color was that participants had also had experience with the majority color. Participants in the feature search condition may have had an attentional set that included the color of the target, since that was consistent. Since the same color was used for the target, perhaps in the test phase participants were still exerting top-down attentional control in favor of the target color to a degree that would have prevented interference by the singleton distractor. We wanted to rule out the possibility that participants who had been trained with feature-search trials were searching only among items of the non-singleton color, in which case the resistance to capture would have been due to experience with a feature of the target and not to experience with the salient feature of the color-singleton distractor. To that end, Experiment 2 was nearly identical to Experiment 1, but here, in addition, to the shapes changing from training to test the majority color was changed from training to test. Participants might have gone from viewing displays such as either Figure 8A or 8B, during training to ones like 8D at test, rather than to displays like those in 8C.

Method

Participants

Participants were 28 (20 female) Johns Hopkins undergraduates who were compensated with credit. All were at least 18 years of age with an average age of 19.5. All participants reported normal or corrected-to-normal visual acuity as well as normal color vision.

Apparatus

This was the same as in Experiment 1.

Stimuli and Procedures

This was nearly the same as Experiment 1, but the if a participant had blue as the majority color in training it was changed to green for test and if a participant had green as the majority color initially, it was changed to blue for the test phase. Thus, both shape and majority color changed from training to test. The singleton color used was identical in training and test.

Results and Discussion

Mean reaction times and standard deviations are shown in Table 2. For the training phase, there was a main effect of the color singleton such that participants took longer to respond when the color singleton was present in the display, $F(1,26) = 61.19$, $p < .001$. There was also a main effect of search mode such that participants were slower in the singleton detection condition, $F(1,26) = 63.16$, $p < .001$. The search mode manipulation appeared to have been effective since there was a significant interaction between search mode and presence of a singleton distractor, $F(1,26) = 42.35$, $p < .001$, such that participants experienced more distractor interference in the singleton-detection condition.

Color Singleton	Absent	Error Rate (%)	Present	Error Rate (%)
Training				
Feature	729(106)	3.0	742(123)	3.2
Singleton	1126(171)	7.2	1269(204)	9.6
Test				
Feature	779(155)	2.5	771(151)	3.0
Singleton	812(170)	2.4	838(192)	4.0

Table 2. Mean color singleton present and absent reaction times and standard deviations in milliseconds, as well as error rates, for Experiment 2 training and test phases.

During the training phase, the amount of capture during the singleton-detection trials was 142 ms which was significant, $t(13) = 7.697$, $p < .001$. The mean difference between the two conditions for the feature search training trials was 13 ms, which was not a significant amount of capture, $t(13) = 1.800$, $p = .095$. This demonstrates that the two groups were experiencing either capture or a lack of capture as is typical for singleton detection and feature search respectively.

In the test phase (see Figure 9) there was no main effect of presence of the color singleton, $F(1,26) = 1.90$, $p = .179$, or of the type of training, $F(1,26) = .04$, $p = .434$. There was a significant interaction between the type of training and the presence of the color singleton, such that participants who were feature-search trained experienced less distractor interference than those who were singleton-detection trained, $F(1,26) = 6.40$, $p = .018$.

At test, as in Experiment 1, the singleton-detection trained participants experienced a significant mean amount of capture, 25 ms, $t(13) = 2.377$, $p = .034$. The feature-search trained participants did not show a significant amount of capture—in fact the numerical difference was slightly negative, with a mean of -8 ms, $t(13) = -1.012$, $p = .330$. The presence of a color singleton on option trials did not increase the response times of feature-search trained participants, as it did for the singleton-detection trained participants, which means that even with both the shape set and majority color changing from training to test, and only the color of the color singleton distractor remaining consistent, there was a distinct difference in the way participants responded to the option trials due to the type of training they received. In the case of the singleton-trained participants, the continuing presence of capture could have been due to the transfer of singleton search mode or to singleton detection mode being the default for option trials. For feature-trained participants, the resistance to capture almost certainly did transfer, since a lack of capture on option trials would conflict with previous findings (e.g., Theeuwes, 1992) and feature search is not assumed to be the default search mode.

As seen in Table 2, the error rates did not show evidence of any speed-accuracy tradeoff. Overall, the response times were very similar to Experiment 1, though a bit slower in a few conditions.

Experiment 3

Singleton detection is often discussed as the 'default' search mode (Bacon & Egeth, 1994; Leber & Egeth, 2006a), despite the fact that reaction times to singleton-detection displays are not necessarily faster than those to feature-search displays, meaning that there is no concrete evidence that feature searches are in some way easier. In Experiments 1 and 2, and in previous studies (Leber & Egeth, 2006b), feature-search trials were significantly faster during training. In fact, under operant condition training designed to encourage the use feature search mode on option trials, participants still experience attentional capture, showing no evidence of having adopted a feature search even when they explicitly claim to be using a feature search strategy (Kawahara, 2010). To confirm that singleton detection is the default mode on option trials, in particular option trials with the shapes used here, and determine the magnitude of capture, participants were given the test portion of the previous experiments without any training.

Method

Participants

There were 18 participants in total (13 female): 4 were members of the Hopkins community who participated for $5 compensation and 14 were undergraduates who participated for credit. All were over 18 years of age with an average age of 19.4.

Apparatus

This was the same as in Experiment 1.

Stimuli and Procedures

Stimuli and procedure were identical to Experiment 1, but without any training. Participants were simply given the 20 practice trials and 320 experimental trials of the test portion, making this a half-hour long experiment.

Results and Discussion

The average response latency was 758 ms (sd = 104.3 ms) for distractor absent trials and 776 ms (sd = 113.4 ms) for distractor present trials. The mean amount of capture was 18 ms (sd = 25.6 ms, $t(17) = 3.021$, $p = .008$). The error rate for both types of trials was 4.5%.

The presence of significant attentional capture suggests that the assumption that singleton-detection mode is the default for option trials is correct. Even when observers are explicitly informed that the target has a consistent feature, they do not appear to adopt that feature as their attentional set in the absence of a prior search where feature-search mode is required. The reason why is not yet known, but perhaps singleton detection is a simpler attention control setting than being set for a specific feature, is the one that provides less strain on cognitive resources, or is the one that is active when observers are not doing a specific task but need to prioritize any unusual visual stimulus because it might signal a behaviorally relevant change in their environment.

One thing to bear in mind is that the amount of capture on these option trials was less than that found in the previous experiments for option trials when participants had received singleton-detection training (see Figure 9). This could be due to simple variability or the confound of having had no prior, possibly fatiguing, cognitive task as there was in the experiments with a training phase. It could also be a meaningful difference, which would mean that a mixed strategy is the default and observers are biased toward one strategy or another by the training. It could also have arisen from a slow transition from singleton-detection mode to feature-search mode as participants became more familiar with the consistent target shape. To test this possibility, the trials were divided into eight bins and analyzed over time. The interaction of time and presence of the distractor was not significant. Overall, as seen in Table 3, the amount of capture had high variability and there was no interaction between the bin number and amount of capture, $F(7,119) = 1.61$, $p = .330$.

Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8
32	34	8	-7	7	-3	26	35

Table 3. Mean amount of capture in milliseconds for the eight bins of Experiment 3.

General Discussion

When considered together, the results of these three experiments converge on the idea that it is resistance to capture by a particular color that transfers within the additional singleton paradigm. With singleton detection training as well as in the absence of any training, participants experience capture by color singletons during the test phase option trials. Previous studies showed that changing the color singleton of the distractor from training to test resulted in a lack of transfer (Zehetleitner et al., 2012), that is, there was significant capture at test even when subjects received feature search training. The studies reported here, where transfer occurs even if the shape and color of the target are changed from training to test, demonstrate that consistency of the salient feature of the color singleton was not only necessary, but sufficient, for transfer to occur.

When the target changed from a circle to a cross, transfer did occur, even though the content of the attentional set for search must have changed, in terms of the shape of the target, but color may also have been part of the top-down control settings. Although in Experiment 1 the target was not defined by being a particular color, it was the same color on all of the trials. It is possible that observers could have included this non-singleton color in an attentional set and excluded other colors from search, thus avoiding capture without this resistance being tied to features of the color-singleton distractor. In Experiment 2, to eliminate this possibility, the color of the target and the majority of the non-targets was changed from training to test. Again, resistance to capture by the salient singleton did transfer. However, transfer did not occur in a previous study when the non-singleton color remained constant, but the singleton color did not (Zehetleitner et. al, 2012). The success of transfer must be tied to the consistency of the color of the additional singleton distractor.

This result cannot be explained by the transfer of a positive attentional set containing the target feature any more than it can be explained by the attentional window hypothesis. A dimensional weighting account cannot explain the results of these studies if it depends on the enhancement of the shape dimension. According to the dimensional weighting hypothesis, observers use top-down control to prioritize a particular feature dimension, which is first checked for the target (Müller, Heller, & Ziegler, 1995). De-weighting of the color dimension, which carries no useful information, would also not explain the results because then a color change to the singleton distractor would not affect whether transfer of search modes occurred. However, one interpretation of dimensional weighting includes broad color categories as sub-dimensions (Found & Müller, 1996). The four colors used in this experiment corresponded to broad color categories, rather than being close in color space. Therefore, it is possible that the broad color category of either red or yellow was de-weighted due to the 0% likelihood that an item of that color would be the target.

In the case of the Zeheitletner et al. (2012) study, a flexible system that operated on a trial-by-trial basis would have de-weighted the color category of the color singleton during training, so capture by the color singleton would not occur. At the beginning of the test trials, the color of the new color singleton would be given its default weighting. Since these trials were option trials, the participants may have found the target through bottom-up saliency without exercising top-down control, and therefore without having to change any of the priority weightings. In the studies presented here, the initial de-weighting could have persisted because the color singleton continued to be the same color and continued to be a non-target item, maintaining its low priority.

A final caveat is that when observers are presented with option trials and do not experience attentional capture, it may not be fair to say that they are still in feature-search mode. After all, experience with feature search without color singletons was not enough to eliminate capture on option trials with singletons (Zehetleitner et al., 2012), so it may not be correct to say that the search mode is transferring. Perhaps it is fairer to say that the suppression that develops during one type of search, but not the other, is able to persist during option trials. It is also the case that whether capture occurs on option trials can depend on the type of training associated with a task-irrelevant background context (Cosman & Vecera, 2013a), which is not compatible with the idea of explicit search modes or ones that arise solely in response to task demands. The results of this study indicate that perhaps learned suppression of a certain feature occurs in response to the context it is associated with, rather than merely persisting when possible. The fact that what transfers is not a goal set, but the suppression of a specific color, seems like evidence against the search mode account, but the difference between types of searches, if not precisely ‘search mode,’ is key to explaining these results. If the type of search did not matter, why would observers learn to suppress a distracting color when the target had a consistent feature but not when the target was defined by its singleton status?

The main issue that any comprehensive explanation of the transfer of training in the additional singleton paradigm has to resolve is why this suppression, or de-weighting, arises only during feature searches, and not when the target is found by singleton detection. Although the target is not consistent during singleton detection training, the color of the additional singleton distractor is consistent, just as it is during feature search training. It has a consistent shape and occurs just as frequently in both types of training. There must be some difference between the mechanism used for singleton detection and that used for feature search, which allows suppression of a specific color to occur only in the latter case.

One possible explanation for the difference relates to the idea that during singleton-detection trials, observers can only set themselves to detect singletons in general and not shape singletons specifically, leading to color singleton capture. Perhaps it is not possible to suppress color singletons without suppressing shape singletons. However, it is not clear why the suppression of a particular color would interfere with the ability to detect any shape singleton. It could be that on feature-search trials, formation of an attentional template and comparison to the stimuli is only happening along the dimension of shape, allowing learned suppression of a specific color to take place, while this learning cannot occur when the target is a singleton and the system is set to detect singletons along any dimension including color. Or, to phrase the previous idea in terms of the dimensional weighting account, in both singleton detection trials and option trials the target can be detected without strong top-down settings, so perhaps the priority weights do not change during these trials and capture will only be overridden if the priority of the otherwise distracting color has already been reduced.

It remains to be see how precisely the suppression of the color singleton is tuned. It is possible that the suppression after experience with a red singleton would apply to, say, reddish-orange or yellowish-orange? It might if the tuning of the suppression was broad enough, or if what was learned was the suppression of more-red-than-target colors. Becker, Folk and Remington (2010) found that with a spatial cuing paradigm, a singleton cue can capture attention because of its relationship to the target (e.g., redder) even if its specific feature value makes it less similar to the top-down target template than the other cues. While the color of the majority of the stimuli was varied here in order to show that the color of the target was not important, there does remain a possibility that if, instead of using colors far apart in color space, we had used majority yellow with say, an orange distractor for training and majority red with an orange distractor for test, the orange distractor would capture attention because the observer learned to suppress more reddish items, and orange is less reddish than red.

Chapter 3: Does resistance acquired during feature search transfer to singleton detection?

Experiment 4

Previous studies of additional singleton transfer (e.g. Leber & Egeth, 2006a, 2006b) were based on the idea that differing search strategies, or modes, were used for singleton detection trials and feature search trials. These modes were considered the result of task demands and either led to capture by irrelevant singletons or resistance to capture. Therefore, the experiments were designed to see whether the search mode would transfer from a task that required that search strategy to one where it was optional. However, the transfer studies discussed previously in Chapter 2 demonstrated that learned resistance to capture by a singleton distractor's color value (e.g. red) or possibly its relational value (e.g. redder) was specifically what was transferring between feature search training trials and option test trials. In that case, it might not be that important for the test phase to involve trials that allow for more than one search strategy.

It has been found (see Experiment 3 or indeed any study using singleton detection trials with a consistent target such as Theeuwes, 1992), that resistance to capture does not arise during option trials by themselves. When we find examples of transfer to option trials it is not the transfer of a search mode, it is a transfer of the learned resistance to capture by a particular color, and this learning is still effective after a switch from feature search trials to option trials. If option trials do not lead to learning, but allow previous learning to remain in effect, perhaps learning acquired during feature search could also transfer to singleton detection trials. After all, if some aspect of employing a feature search strategy permits learned resistance to capture while a singleton detection strategy does not, it does not necessarily follow that previously learned resistance to capture cannot transfer to singleton detection trials.

This study will be based closely on Leber and Egeth (2006b), with feature search trials as the training and singleton detection trials as used in their training phase substituted for the option trials of the test phase. The singleton detection trials will be similar to those used in that study, where the target can be one of several possible shapes (circle, diamond, or triangle), but the non-targets are always a consistent shape (square). The color singleton will have the same feature value (red) in both the training and test phases. In addition there will be two control conditions, one in which the training consists of feature search trials with no color singletons and one in which the singleton color used during training (blue) is different from the singleton color used in the test phase (red). See Figure 10 for an overview of the conditions.

We hypothesize that resistance to capture cannot develop during singleton detection trials, but can transfer from feature search to singleton detection, and that participants who experience feature search training with a red distractor will experience zero or minimal capture by a red color singleton during singleton detection test trials. We would expect the no-distractor feature search training to have no effect on the test trials because experience with a particular distractor appears to be key in resisting distraction, and in that condition no experience with resisting capture can be gained during training. This means we expect there to be significant capture by the singleton, in the range of around 50 ms to 150 ms as typically found during singleton detection. We also expect that exposure to the different color distractor in training will have no effect on the test phase, and there will be similar levels of capture in the different color distractor condition and the no-distractor condition. However, it is possible that experience with the blue distractor will lead to an intermediate magnitude of capture, which would indicate that experience with color singleton distractors in general has a role in overcoming capture by color singletons.

It is also possible that we will not be able to reject the null hypothesis, which is that experience with different types of feature search training have no effect on the amount of capture during singleton detection trials. In this case we expect the amount of capture to be significant, of similar magnitude to other singleton detection studies, and no different between groups. This would mean that resistance to capture only transfers to option trials, not trials where singleton detection is the only viable strategy.

There is one more outcome that could be important, which is that all the groups would experience no capture, or minimal capture (say, no more than 20 ms), during the test phase. However, neither feature search theory nor a distractor experience theory would explain that result, since feature search mode cannot be used on this type of singleton detection trial and the different conditions provide different types of distractor experience. More control conditions would need to be run before such a result could be meaningfully interpreted.

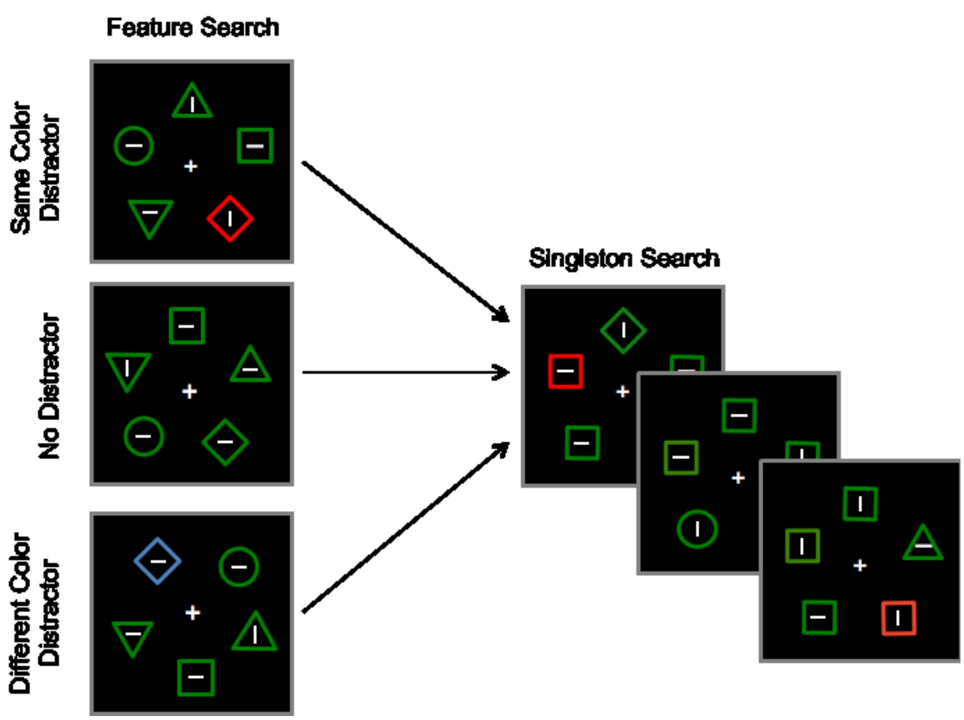

Figure 10. The three types of displays on the left represent the different training conditions for the three different groups, and the display on the right represents three examples of singleton test trials. The target was the circle during training and the uniquely shaped item at test.

Method

Participants

Participants were 36 (13 male) Johns Hopkins University undergraduates with a mean age of 19.9 who participated in return for extra credit. An equal number of participants were assigned to each condition, but data from one participant in the different color distractor condition was lost due to a computer error. Data from one participant in each condition was excluded due to accuracy below 70% on at least one type of trial. Participants were all over the age of 18 with normal or corrected-to-normal vision.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920x1080 resolution and a screen refresh rate of 60 Hz, which was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the ‘h’ keyboard key for horizontal or ‘v’ key for vertical.

Stimuli

Each display consisted of five or nine outline shapes equally spaced around an imaginary circle, 3.5º from the center of the display to the center of each shape, each of which contained a horizontal or vertical white line in the center. Each shape outline was .1º thick and the line inside was .5º in length and .05º in thickness. The line inside each shape had an equal probability of being horizontal or vertical. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. On singleton-absent trials, the outline shapes were all green in color (RGB: 0, 153, 0).

The feature search displays were similar to those used by Leber and Egeth (2006b). The shapes were a circle (diameter 1.5º), diamond (sides 1.3º), square (sides 1.3º), upward pointing equilateral triangle (sides 1.5º), and downward pointing equilateral triangle (sides 1.5º). If there were nine items in the display, the additional shapes were all diamonds. The target was the circle and if a color singleton was present it was one of the diamonds. In the same color distractor condition the color singleton was red (RGB: 255, 0, 0) and in the different color distractor condition the color singleton was blue (RGB: 0, 128, 255).

The singleton detection displays were similar to those used by Leber and Egeth (2006b). The non-target shapes were squares with sides measuring 1.3º. On each trial the target had an equal probability of being a circle (diameter 1.5º), diamond (sides 1.3º), or an upward pointing equilateral triangle (sides 1.5º). The color singleton was red (RGB: 255, 0, 0). If a color singleton was present in the display, it was one of the non-target squares.

<u>Design and Procedure</u>

In the training phase, participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the uniquely shaped item as quickly and accurately as possible. They were instructed that they would receive feedback for wrong answers and that various colors and shapes might appear during the course of the experiment, but that the task would still be to look for the circle.

The instructions and procedure were the same for the three conditions, only the presence or type of color singletons differed. In the same color distractor condition, the color singleton distractor was red and appeared on half of all trials. In the no-distractor condition, there were no color singletons at all. In the different color distractor condition a blue color singleton appeared on half of the trials.

Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks throughout the experiment. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance. Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response or responded after 2,000 ms, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The training phase was 480 trials long, which took most participants about 25 minutes.

In the test phase, the instruction was to search for the uniquely shaped item. The target could be a circle, a diamond, or a triangle. There were only 6 practice trials. The color singleton distractor was red and appeared on half the trials. Everything else was the same as the training phase.

Results

Training Phase

See Table 4 for the raw response times from the three training conditions, as well as the error rates. Data from the three training conditions were analyzed separately since the no-distractor condition could not be directly compared to the two conditions where a distractor was sometimes present.

Response times from the same color distractor condition were entered into a 2 (distractor presence) x 2 (display size) within-subjects ANOVA. The main effect of distractor presence was not significant, $F(1,11) = 3.80$, $p = .080$. The numerical value of the magnitude of capture was 13 ms, but the fact that it was not significant is what we would expect from feature search trials. The main effect of display size was significant, $F(1,11) = 14.54$, $p = .003$, such that participants were slightly slower with a larger display size. The difference worked out to a 10.3 ms/item cost, which is not unusual for feature search trials and still indicates an efficient search. The interaction between distractor and display size was not significant, $F(1,11) = 0.12$, $p = .573$.

	5 Items		9 Items	
	RT	Error	RT	Error
Same Color Distractor				
Distractor Absent	719(92)	5.2%	758(109)	4.3%
Distractor Present	729(98)	4.3%	772(122)	4.2%
No Distractor				
Distractor Absent	796(100)	3.6%	825(117)	3.0%
Different Color Distractor				
Distractor Absent	780(124)	3.3%	810(158)	3.5%
Distractor Present	772(109)	3.9%	820(154)	2.3%

Table 4. Mean response times in milliseconds with the standard deviations in parentheses for the training phase, as well as the percent error rates.

Response times from the no-distractor condition were entered into a one-way within-subjects ANOVA to look at the effect of display size. There was a 7.3 ms/item search cost and the difference between 5 items and 9 items was significant, $F(1,9) = 11.97$, $p = .007$.

Response times from the different color distractor condition were entered into a 2 (distractor presence) x 2 (display size) within-subjects ANOVA. There was no main effect of distractor presence, $F(1,8) < 0.01$, $p = .951$. In this condition there was 0 ms of capture, which is exactly what one would predict for feature search. The main effect of display size was not significant $F(1,8) = 5.05$, $p = .055$. Since this was a marginal effect, we calculated the cost to be 10 ms/item, which was similar to the same color distractor training. The interaction between distractor and display size was not significant, $F(1,8) = 1.13$, $p = .318$.

Feature Training Type	5 Items RT	5 Items Error	9 Items RT	9 Items Error
Same Color Distractor				
Distractor Absent	832(141)	4.8%	831(151)	4.7%
Distractor Present	894(152)	7.2%	910(158)	6.7%
No Distractor				
Distractor Absent	874(142)	5.4%	829(114)	3.8%
Distractor Present	963(200)	5.9%	940(151)	6.3%
Different Color Distractor				
Distractor Absent	923(136)	6.6%	909(161)	4.6%
Distractor Present	1,006(150)	7.0%	999(182)	5.9%

Table 5. Mean response times in milliseconds with the standard deviations in parentheses for the test phase, as well as the percent error rates.

Test Phase

See Table 5 for the raw response times, as well as the error rates, from the test phase. Response times were entered into a 3 (training condition) x 2 (distractor) x 2 (display size) mixed ANOVA. There was no main effect of training condition, $F(2, 29) = 1.01$, $p = .374$, on overall response times. There was a main effect of distractor, such that response times were 86 ms slower when the distractor was present, $F(1,29) = 64.82$, $p<.001$. This means that the color singleton captured attention, as would be expected for option trials in the absence of effective training. There was no main effect of display size, $F(1,29) = 2.31$, $p = .139$, which is what was expected from a pop-out target that could be searched for in parallel.

The key interaction between training condition and distractor presence was not significant, $F(2, 29) = 0.67$, $p = .519$, so we could not reject the null hypothesis. The magnitude of capture was 71 ms in the same color distractor condition, 100 ms in the no-distractor condition, and 86 ms in the different color distractor condition, so while there were numerical differences in the magnitude of capture, the means were within the range typical for singleton detection search and nowhere near the lack of capture that was obtained in the feature search training. Different types of feature search training did not affect the magnitude of capture on the singleton detection trials.

There was no two-way interaction between condition and display size, $F(2,29) = 2.28$, $p = .120$, or between distractor and display size, $F(1,29) = 2.16$, $p = .152$. There was no significant three-way interaction between condition, distractor and display size, $F(2,29) = 0.16$, $p = .857$.

Discussion

It appears that resistance to capture that exists during feature search does not transfer to singleton detection trials. This result can easily be explained under search mode theory, since feature search mode cannot be used on trials where the target is an unpredictable shape singleton, and capture by a salient color singleton is predicted during the search for any type of less salient singleton. However, since experience-based theories of attentional capture, such as dimensional weighting (Müller, Reimann, & Krummenacher, 2003) seem to be supported by recent studies (e.g., Vatterott & Vecera, 2012; Zehetleitner, Goschy, & Müller, 2012), it makes sense to consider the present result in light of such theories.

On one level it seems logical that under circumstances where attentional capture is typically quite strong and occurs across hundreds of trials, learned resistance to capture would not be able to overcome the circumstances that were leading to attentional capture in the first place. However, we know from studies such as Leber and Egeth (2006b) that resistance to capture can transfer from feature search training to option test trials. Option trials are actually the same as the typical original trials of the additional singleton paradigm (for example, Theeuwes, 1992), and there has been a robust finding of capture on many studies using these types of trials. Individual trials for both singleton detection and option look the same. The only difference is the context of the overall block, since in the option version the target shape is consistent and in the singleton detection version the target is unpredictable. Therefore, there may be an important role of search strategy, such that learned resistance to a certain potentially distracting feature value is tied to the use of a feature search strategy. When a feature search strategy is not possible, the learned resistance to capture will not transfer.

It could also be that resistance to capture is tied to a particular context, rather than a particular strategy, which could also explain the results of Cosman and Vecera (2013a) who found that different types of training paired with a certain type of background context led to capture on option trials with the background type associated with singleton detection but not those with the background type associated with feature search. Perhaps here, the sudden switch to the context of searching for an unpredictable target was too different for prior learning to have an effect.

Follow-up studies could provide further evidence that the lack of an effect of training on capture obtained here was truly a null effect. One possibility would be to compare the effects of singleton detection training or no training with the effect of feature search training. The test phase could either be singleton detection test trials or option test trials, resulting in four conditions in total. Based on the present results we would expect that at test there would be no capture for feature-training/option-test participants, while there would be significant capture at test for feature-training/singleton-test, singleton-training/singleton-test, and singleton training/option-test participants. If the present results missed a real difference between same color distractor training and no-distractor training, or if experience with feature search is by itself enough to lead to reductions in capture, with enough participants we might see that feature training did have some effect on singleton test trials when compared to the case where participants only performed singleton detection throughout the experiment.

Based on the results of this experiment, it appears that feature training cannot lead to the elimination of or significant reduction of attentional capture on additional singleton trials where a singleton detection strategy is required. This is one way in which such trials are different from option trials where either feature search or singleton detection could be used. These results indicate that search strategies have an important influence on attentional capture, even if some of the tenets of search mode theory do not hold. It remains to be seen if there are any circumstances under which past experience, rather than the physical properties of the stimuli can either reduce or enhance the magnitude of capture obtained on trials where a singleton detection strategy is mandatory.

Chapter 4: Can attention be captured during feature search?

In contrast to trials on which observers can employ a singleton detection strategy, observers who search for a known shape that is not a shape singleton do not experience attentional capture (Bacon & Egeth, 1994). Search mode theory explains this result in terms of participant's search strategy. When participants are searching for a specific shape they will not be subject to capture by any type of singleton because singletons are not pertinent to their current task goals.

On the other hand, stimulus-driven accounts of capture argue that capture does not occur because this is not a perfectly parallel search with a target that "pops out" (Theeuwes, 1994), since as discussed in Chapter 1, Bacon and Egeth did not find a perfectly flat search slope during feature search. Under the attentional window account, the color singleton does not capture attention because the heterogeneous display causes the attentional window to shrink and the color singleton does not usually fall inside the window at the same time as the target.

What both accounts have in common is that they predict that during feature searches among heterogeneous shapes the color singleton distractor in a sense does not matter, either because the color singleton is irrelevant to the task or because the attentional windows size is too small to lead to a measurable capture effect. However, there is reason to believe that attentional capture can occur on feature search trials, as in the initial trials of Vatterott and Vecera (2012), and this is best explained by experience-dependent accounts of capture.

Chapter 2 already described evidence for experience-dependent accounts of learning using the Leber and Egeth (2006b) transfer paradigm. Evidence for feature-specific learning (referred to by the authors as experience-dependent attentional tuning) during feature search comes from Vatterott and Vecera (2012). In Experiment 1 of their study, they changed the color of the color singleton after each 48 trial-long block. They analyzed the first and second halves of each block and found that there was a significant amount of capture on the first half, but not on the second half. Experiment 2 was similar except that they eliminated rest breaks, and showed the same result. There are two important conclusions to be drawn from this. The first is that the lack of capture during feature search is not automatic or the result of a single trial, though it does develop relatively quickly. The second is that the experience that allows lack of capture to develop has to be with a certain feature value, not just any color of color singleton, otherwise changing the singleton color would not result in a period of measurable attentional capture.

While Vatterott and Vecera provided strong evidence for the importance of experience with the color singleton, the speed of this learning means that capture can only be detected on a few trials. They averaged the first 24 trials, so it may be that capture only occurs on even fewer of the initial trials and is presumably decreasing over time. It would be difficult to take a measure of the magnitude of attentional capture expected on feature search trials using their paradigm. We wanted to create a paradigm in which capture would occur during an entire experiment lasting hundred of trials both to show that capture would not be eliminated due to experience with feature search in general and so that we could take a reliable measure of its magnitude.

In order to do so, the current study uses feature search trials where the task was to look for a circle, but the trials are arranged in such a way that participants cannot learn to associate particular colors with the target and salient distractor. One group of participants experienced the typical fixed color condition and one experienced a color-swapping condition, in which the color of the majority of the items could switch with the singleton color between trials. That is, on one trial the majority of items could be green and the distractor red, and on the next trial, the majority could be red and the distractor could be green. In the color-swapping condition participants would not be able to associate a particular feature value with the color singleton, and any learning that occurred over a few trials would presumably be wiped out as soon as a color switch occurred, as it was in Vatterott and Vecera's (2012) experiment after a change in the color of the color singleton. We predict that attentional capture will occur only in the color-swapping condition, not the fixed color condition.

We also want to probe the limits of resistance to capture by testing the case where the majority color varied from trial to trial, but the singleton color did not, as well as the case where the singleton color varied, but the majority color did not. We do not expect capture to occur in either of those conditions, since we do not think experience with the majority color is important for resisting capture (as long as it is never used as the singleton color) and because we think that it should be possible to learn to resist at least a few colors at the same time as long as those colors never become associated with the item that must be attended.

The current study also allows us to determine whether it is proper to say that capture is *resisted* on feature search trials, which is the term used by Bacon and Egeth (1994). It would not be correct to say that capture is resisted if there are no conditions under which capture by an irrelevant color singleton would occur during feature search trials. We believe that capture is resisted, rather than simply lacking, and that this resistance is learned, not automatic. Attentional capture will take place on such trials when feature-specific learning is prevented.

It is likely that intertrial priming would affect response times and quite probably the magnitude of capture, such that participants would be faster when the previous trial had the same majority color and slower when the previous trial had a different majority color. After a swap trial, we predict that participants will be slower if a distractor had been present on the previous trial than if the previous trial had not contained a distractor. This is because participants might have been inhibiting the previous distractor color in some way they and they would have to overcome that inhibition in order to attend to the target. We also predict that participants will experience more capture on distractor-present trials after a color swap than after a same-color trials because the distractor color is now associated with successfully finding a target, and attention will be strongly drawn to it. We expect that participants will experience the least attentional capture by a singleton after same-color trials with a distractor because of the recent experience with a distractor of that color.

A phenomenon from outside the additional singleton literature that is relevant to our examination of intertrial priming is priming of popout. Priming of popout (PoP) is the term used by Maljkovic and Nakayama (1994) to describe a phenomenon whereby observers are faster to find color singleton targets when the colors of the target and distractors match those on previous trials. This is a type of learning that is short-term and implicit. The effect is cumulative and reaches its maximum point after around eight trials, or approximately 30 seconds. It occurs for both the target and distractor feature values independently, but is stronger for the target. It is thought to have a functional role for directing eye movements. PoP is important to consider in relation to the additional singleton paradigm because the target is a singleton, and in some versions of the additional singleton paradigm the target and non-targets can swap shapes from trial to trial.

Of course, in the additional singleton paradigm, the color singleton distractor is to be avoided while the popout target is a shape singleton, which complicates matters. In the feature search version, participants can find the target very efficiently, and since the target remains the same shape throughout the experiment, shape priming would not be a factor unless target shape changes were somehow introduced. Priming related to the singleton and majority colors, however, is likely to matter, though it is hard to say if we would expect it to behave similarly to classic PoP. Among the obvious differences is that while the color singleton in the additional singleton paradigm does seem to pop out in the display, it is never the target and it is not present on every trial.

Several studies have examined priming in the additional singleton paradigm in order to see whether it can explain why the magnitude of capture found on trials with an unpredictable shape singleton target is greater than that found on option trials with a fixed target. Pinto, Olivers, and Theeuwes (2005) argued that the difference was due to intertrial priming, rather than uncertainty about the upcoming target. They looked at the trials where the target and non-target shapes could swap identity from trial to trial, called the mixed condition, and divided them into those that were preceded by a trial with the same mapping of shapes to the target and non-targets and those that were preceded by a trial with a different mapping. They found that the magnitude of capture was less on trials preceded by a trial with the same mapping. In fact, the magnitude of capture on the subset of mixed trials not preceded by a shape change was the same as that obtained in the fixed target shape condition. They concluded that the greater magnitude of capture found in the mixed condition overall was due to the priming-related switch cost on trials preceded by a different shape mapping.

In contrast, Lamy, Carmel, Leber & Egeth (2006) came to the conclusion that differences between the magnitude of capture in the fixed and mixed target shape conditions were more likely due to differences in search strategy than to priming. They varied the lengths of runs of same-shape target trials in the mixed target condition and found that increasing the length of the run did not lead to reduced attentional capture. Because PoP is cumulative, the authors rejected this explanation of the findings and favored a search mode account, proposing that when the target shape was repeated, participants would use a partial feature search strategy, leading to reduced capture. In Pinto et al. the distractor-present and distractor-absent trials were in different blocks, while they were intermixed in Lamy et al., which could have led participants in Pinto et al. to change their search strategy between blocks.

In the following experiments, since the target will always be a circle, any priming effects would be due to the colors rather than the shapes. Based on the prior research, we expect that intertrial priming may affect the magnitude of capture, such that after a color swap has occurred, participants will experience a greater magnitude of capture. However, we do not think this will entirely explain findings of capture in the color-swapping condition, if indeed capture occurs at all in that condition. We predict that participants' inability to form an association between the color singleton and a specific color will lead to capture. Color uncertainty from trial to trial will not lead to capture as long as there is no overlap between majority colors and singleton colors.

Experiment 5

In Experiment 5, participants searched for a target defined by its shape (a circle) in a display that contained several other shapes. We used a paradigm related to the one used in Pinto, Olivers, and Theeuwes (2005) and Lamy, Carmel, Leber and Egeth (2006), but with possible color uncertainty rather than shape uncertainty. In the color-swapping condition, the majority color, that is the color of all items except for the color singleton, could have one of two possible values and if a singleton was present it had the other of those two colors. The current majority color had an equal probability of being the same as or different from the previous trial's majority color. That is, the feature values of the majority color and singleton color could randomly switch from trial to trial (see the lower half of Figure 11). In the fixed color condition the majority color had the same value throughout the experiment, as did the singleton color. This is the same as typical feature search trials.

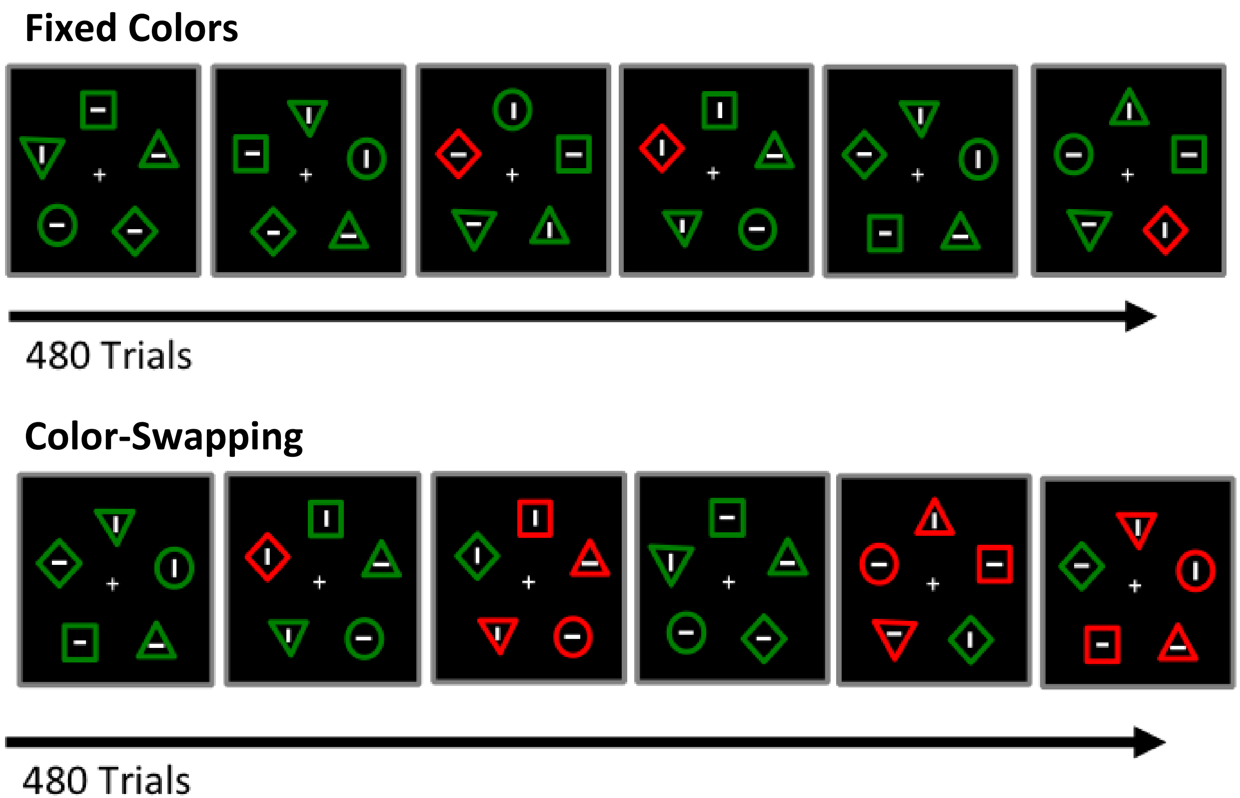

Figure 11. Example trials for Experiment 5, where the target was always the circle. In the fixed condition the displays were always a particular color throughout the experiment (green majority color, as here, or red majority color), although there could be a color singleton distractor present in the display. In the color-swapping condition displays could be either red or green, as could the color singleton distractors. Some trials in the color-swapping condition could have a completely different color mapping, as in the second and third displays, while some were the same, as in the fifth and sixth displays.

We anticipated that there would a significant amount of capture in the swapping condition, but not in the fixed condition, because participants in the swapping condition would not be able to benefit from past experience with a specific color of distractor the way participants in the fixed condition could. We also thought that the magnitude of capture in the fixed condition would be similar to the magnitude of capture found on option trials, that is singleton detection trials with a fixed shape target, but less than the usual magnitude of capture with a fixed target. We also anticipated an effect of intertrial priming, but that capture would not be entirely explained by whether the previous trial was same or different.

In terms of intertrial priming, we specifically predict longer response times after a swap, due to a cost of switching to search for a target with a different color. We also predict two ways that the previous trial will affect the magnitude of capture on the current trial. We predict that the magnitude of capture on the current trial will be greater when the previous trial had a different majority color than when it had the same majority color, because in the former case participants will be primed to search for the previous trial's majority color, which is now the singleton distractor color. We also predict that the magnitude of capture will be less when the previous trial's majority color matches the current majority and a distractor was present on the previous trial because in this case participants might be inhibiting the singleton distractor color as well as attending to the majority color.

Method

Participants

Twenty-four (ten male) Johns Hopkins University undergraduates with a mean age of 19.5 years participated in exchange for extra course credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. Half were assigned to the color-swapping condition and half were assigned to the fixed color condition.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920x1080 resolution and a screen refresh rate of 60 Hz that was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the 'h' keyboard key for horizontal or 'v' key for vertical.

<u>Stimuli</u>

Each display consisted of five outline shapes equally spaced around an imaginary circle with a radius of 3º from the center of the display to the center of the shapes, each of which contained a horizontal or vertical white line in the center. Each shape outline was .1º thick and the line inside was .5º in length and .05º in thickness. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. The shapes were a circle (diameter 1.5º), diamond (sides 1.3º), square (sides 1.3º), upward pointing equilateral triangle (sides 1.5º), and downward pointing equilateral triangle (sides 1.5º). The outline shapes could be either red (RGB: 255, 0, 0) or green (RGB: 0, 255, 0) in color. If a color singleton was present in the display, it was always the diamond, while the circle was always the target.

<u>Design</u>

Half the trials in all conditions were distract-absent and half were distractor-present. These trials were randomly intermixed. On distractor-absent trials, all items were the same color, referred to here as the majority color, which could be either green or red. On distractor-present trials one items was a color singleton, which would be green if the majority color was red or red if the majority color was green. In the fixed color condition, half of the participants were given trials where the majority color was green throughout the experiment and half were given trials where the majority color was red throughout the experiment. In the color-swapping condition, half the trials had a red majority color and half had a green majority color. Each trial in the color-swapping condition was equally likely to have the same or different majority color as the one before it. This means that in the color-swapping condition, green could sometimes be the majority color and sometimes the singleton color, as could red. In both conditions, the lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five possible locations was randomized.

<u>Procedure</u>

Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 480 trials long, which took most participants about 20 minutes.

Results and Discussion

Trials with an incorrect response or no response were excluded from the main analyses. Mean RTs (see Table 6) were entered into a 2 (color mapping group) x 2 (color singleton distractor present or absent) ANOVA. There was no significant main effect of the between-subjects factor of color mapping, $F(1,22) = 1.20$, $p = .286$, although the mean response times were faster in the fixed color condition. There was a main effect of color singleton distractor, indicative of attentional capture, $F(1,22) = 17.32$, $p < .001$, which was driven by the significant interaction between the color condition and presence of the distractor, $F(1,22) = 6.06$, $p = .022$, such that the distractor slowed response times more in the color-swapping condition than in the fixed condition, as predicted. Error rates were very similar across conditions, so the difference in response times cannot be explained by a speed-accuracy tradeoff.

	Response Time (ms)		Error Rate (%)	
Color Singleton	Fixed Color	Color-swapping	Fixed Color	Color-swapping
Absent	686(95)	718(112)	4.8	4.5
Present	698(99)	764(136)	5.0	4.3

Table 6. Mean color singleton present and absent reaction times and standard deviations in milliseconds, as well as percent error rates.

As seen in Figure 12, the mean amount of capture (distractor-present response time - distractor-absent response time) in the fixed condition was 12 ms, $t(1,11) = 1.78$, $p = .103$, which was not significant, as expected from classical feature search trials. In the swapping condition it was 45 ms, $t(1,11) = 3.77$, $p = .003$. This is actually quite similar to the amount of capture

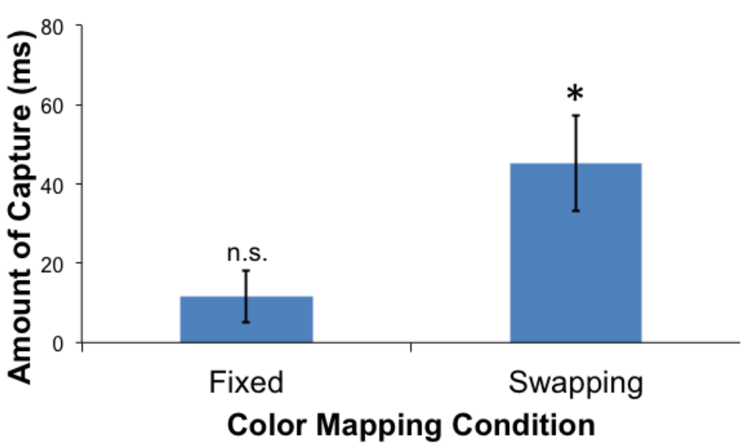

Figure 12. Mean amount of capture in milliseconds for the two different groups in experiment one. The amount of capture was only significant in the swapping condition. Error bars represent the standard error of the mean

typically found on option trials with absent or ineffective training, for example, 40 ms in Experiment 2 of Zehetleitner, et al. (2012) where the training phase did not include any color singleton distractors.

Further analysis of the color-swapping condition

In order to assess the effect of the previous trial in the color-swapping condition, we divided the trials in that condition based on whether there was a color singleton present, whether the majority color on that trial was the same or different as the majority color on the previous trial, and whether a distractor had been present on the previous trial or not. Mean RTs (see Table 7) were entered into a 2 (current trial distractor presence) x 2 (previous trial majority color) x 2 (previous trial distractor presence) mixed ANOVA.

	Previous Majority Color			
	Same		*Different*	
	Previous Distractor			
Color Singleton	*Absent*	*Present*	*Absent*	*Present*
Absent	708(114)	721(123)	750(132)	725(112)
Present	740(124)	750(132)	784(129)	780(165)

Table 7. Mean color singleton present and absent reaction times and standard deviations in milliseconds for the different priming conditions.

There was a main effect of distractor presence in the current trial, $F(1,11) = 14.34$, $p = .003$, indicating robust attentional capture, as expected from the preceding analysis. There was also a main effect of the previous majority color such that response times were slower on trials where the previous majority color was different, $F(1, 11) = 16.57$, $p = .002$. This effect was almost certainly due to color priming.

There was also a significant interaction between the previous majority color and the presence of the distractor such that participants experienced a greater magnitude of capture after a different majority color trial, $F(1,11) = 5.32$, $p = .042$. This indicates that the magnitude of capture was affected by a priming effect possibly similar to that examined in past additional singleton experiments (Pinto et al.,2005; Lamy et al., 2006). This is the starred difference shown in Figure 13.

There was no significant main effect of whether the previous trial had a distractor or not,

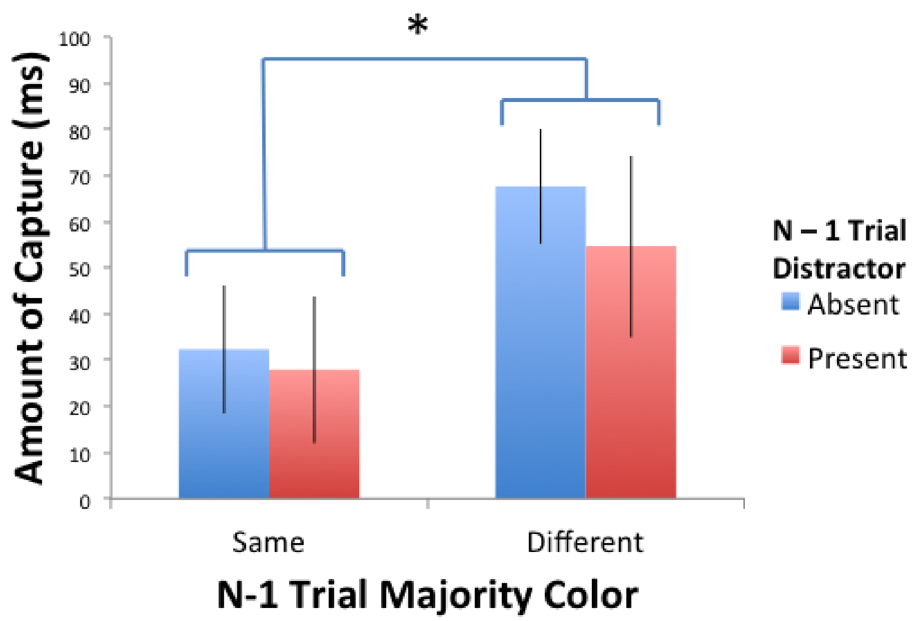

Figure 13. Amount of capture based on the similarity of the previous trial, which could have had either the same or different majority color from the preceding trial, and could have had a distractor on the preceding trial or not. Error bars represent the standard error of the mean.

$F(1,11) = .78$, $p = .397$, no interaction of the presence of the distractor on the previous trial with the previous majority color, $F(1,11) = .43$, $p = .526$, and no interaction of the presence of a distractor on the previous trial with presence of a distractor on the current trial, $F(1,11) = .76$, $p = .403$.

There was no three-way interaction of the previous distractor, previous majority color, and current presence of a distractor, $F(1,11) = .14$, $p = .717$. A significant interaction might have indicated that participants experienced the least capture on trials where the current majority color matched the previous majority color and there was a distractor on the previous trial, that is, when the current distractor is the same color as the distractor on the previous trial. A three-way interaction would have indicated that a substantial degree of resistance to capture was able to develop after a single trial of experience with a particular distractor color as compared to after a trial with the same majority color but no distractor, but this was not the case.

This experiment demonstrates that attentional capture can occur on feature search trials with heterogeneous displays, which is not what search mode theory predicts. In both the fixed condition and the swapping condition, the target was a circle and participants needed a strategy of searching for circles in order to find the target. In the color-swapping condition, the color singleton distractor did not share the target feature, and yet it was able to capture attention. The magnitude of capture in the swapping condition was reduced when the previous trial had the same color mapping, but not eliminated. This is unlike what one would expect to find on typical feature search trials with a fixed color mapping, indicating that not all capture in this condition resulted from a change in the majority color from the previous trial.

Experiment 6

In Experiment 6 we wanted to rule out the possibility that the capture found in the color-swapping condition of Experiment 5 was due to switch costs resulting from changes in the majority color, whether due to intertrial priming or target uncertainty. Although color is not relevant the task, it may be easier to direct attention to the target and avoid capture if the template is ‘green circle’ instead of simply ‘circle.’ When the target template only has one feature, perhaps observers will be less efficient in locating the target and thus vulnerable to attentional capture. Be that as it may, we expected that changing only the majority color would not lead to capture, since Experiments 1 and 2 of this thesis have pointed to the importance of experience with the color singleton distractor, rather than with target features. Because the distractor color was always red in this experiment, as seen in Figure 14, participants should have the experience they need in order to resist capture by that distractor.

Method

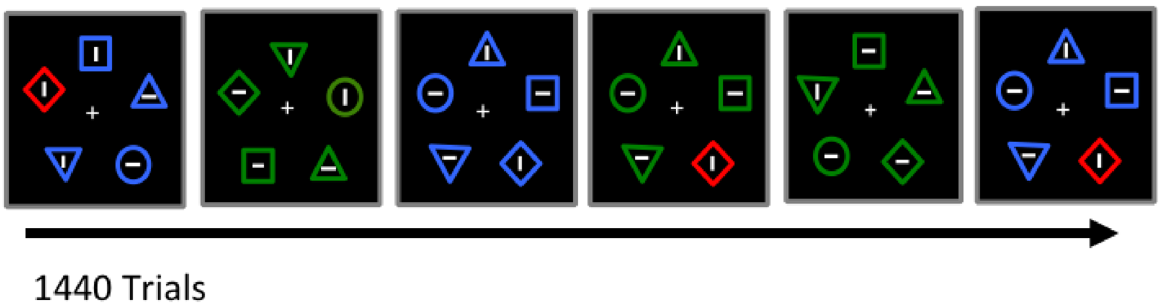

Figure 14. Example trials for Experiment 6, where the target was always the circle. The majority color was randomly either green or blue. Color singletons distractors were present on half of all trials and were always red.

Participants

Sixteen (seven male) Johns Hopkins University undergraduates with a mean age of 19.5 participated in exchange for extra credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. Data from the first four participants was discarded due to a programming error and one participant was excluded from further analysis due to having an overall accuracy of less that 70%.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920x1080 resolution and a screen refresh rate of 60 Hz that was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the ‘h’ keyboard key for horizontal or ‘v’ key for vertical.

Stimuli

Each display consisted of five or nine outline shapes equally spaced around an imaginary circle with a radius of 3º from the center of the display to the center of the shapes, each of which contained a horizontal or vertical white line in the center. Each shape outline was .1º thick and the line inside was .5º in length and .05º in thickness. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. The shapes were a circle (diameter 1.5º), diamond (sides 1.3º), square (sides 1.3º), upward pointing equilateral triangle (sides 1.5º), and downward pointing equilateral triangle (sides 1.5º). When there were five items one of each shape was present, when there were nine items the additional shapes were all diamonds. The outline shapes could be red (RGB: 255, 0, 0), green (RGB: 0, 255, 0), or blue (RGB: 0, 0, 255) in color. If a color singleton was present in the display, it was always one of the diamonds, while the circle was always the target.

Design

In this experiment, the majority color had an equal probability of being green or blue. A color singleton was present on half the trials and was always red. Half the trials had five items and half had nine. The lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five or nine possible locations was randomized.

Procedure

Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 1440 trials long, which took most participants about 50 minutes.

Results and Discussion

The mean RTs (see Table 8) were entered into a 2 (majority color) x 2 (color singleton distractor present or absent) x 2 (display size) repeated measures ANOVA. There was a main effect of majority color such that participants were slower when the majority color was blue, $F(1,10) = 6.73$, $p = .027$. This is almost certainly due to the fact that colors were not luminance matched and the blue subjectively did not stand out as well against the black background as the green. There was no main effect of the presence of the distractor, $F(1,10) = .87$, $p = .372$, which means that participants were able to resist capture. The main effect of display size was significant, $F(1,10) = 13.38$, $p = .004$, which shows that this was not a perfectly parallel search, which is typical of these types of displays. However, the difference between conditions was only 21 ms, which represents a very efficient 5 ms/item cost. Error rates were similar across all conditions, so the differences in response time are not reflective of a speed-accuracy tradeoff.

This experiment demonstrates that the attentional capture found in the color-swapping condition of Experiment 5 was not due to uncertainty about the target color. Although participants could not predict the target's color on a given trial, they might have been able to learn to associate both colors with the target. More importantly, they were able to associate a single color with the distractor, which fits in nicely with an account of attentional capture that is driven by experience with the salient feature of the distractor.

	Response Time (ms)		Error Rate (%)	
	5 Items	9 Items	5 Items	9 Items
Green Majority				
Color Singleton Absent	690(136)	710(128)	5.6	4.9
Color Singleton Present	694(147)	712(126)	5.1	5.4
Blue Majority				
Color Singleton Absent	670(131)	721(135)	5.0	5.2
Color Singleton Present	704(134)	730(137)	4.8	4.5

Table 8. Mean reaction times and standard deviations in milliseconds, along with percent error rates for each condition.

Experiment 7

The purpose of Experiment 7 was to show that even with uncertainty about the distractor color on a given trial, observers would be able to resist capture as long as they had experience with that distractor color, and the color had never been used as a target color. Previous

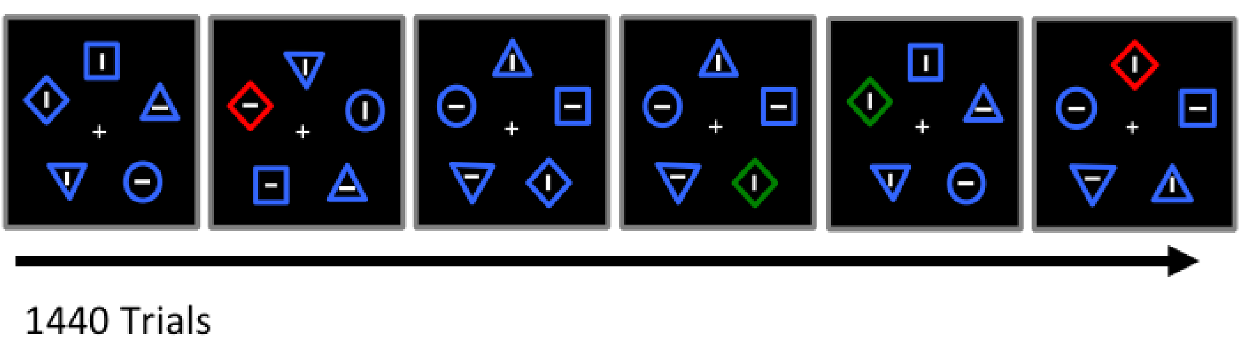

Figure 15. Example trials for Experiment 7, where the target was always the circle. Displays always had a blue majority color. Color singletons distractors were present on half of all trials and could randomly be either red or green.

experiments have demonstrated that this was the case (Vatterott, personal communication), but we wanted to replicate the basic result since data has not yet been published. In this experiment we used two different singleton colors, while the majority color was always a third color, as seen in Figure 15.

Method

Participants

Twenty (seven male) Johns Hopkins University undergraduates with a mean age of 20 years participated in exchange for extra course credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. One participant was excluded from further analysis due to having an overall accuracy of less than 70%.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920x1080 resolution and a screen refresh rate of 60 Hz that was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the 'h' keyboard key for horizontal or 'v' key for vertical.

Stimuli

Each display consisted of five or nine outline shapes equally spaced around an imaginary circle with a radius of 3º from the center of the display to the center of the shapes, each of which contained a horizontal or vertical white line in the center. Each shape outline was .1º thick and the line inside was .5º in length and .05º in thickness. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. The shapes were a circle (diameter 1.5º), diamond (sides 1.3º), square (sides 1.3º), upward pointing equilateral triangle (sides 1.5º), and downward pointing equilateral triangle (sides 1.5º). When there were five items one of each shape was present, when there were nine items the additional shapes were all diamonds. The outline shapes could be either red (RGB: 255, 0, 0), green (RGB: 0, 255, 0), or blue (RGB: 0, 0, 255) in color. If a color singleton was present in the display, it was always one of the diamonds, while the circle was always the target.

Design

In this experiment, the majority color was always blue. A color singleton was present on half the trials and had an equal probability of being green or red. Half the trials had five items and half had nine. The lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five or nine possible locations was randomized.

Procedure

Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 1440 trials long, which took most participants about 50 minutes.

Results and Discussion

All *p* values reported were Geisser-Greenhouse corrected when appropriate. The mean RTs (see Table 9) were entered into a 3 (color singleton type) x 2 (display size) repeated measures ANOVA. There was no main effect of distractor, $F(2,36) = .89$, $p = .400$. Since there was no difference between the distractor-absent trials, the green distractor trials, and the red distractor trials, it is evident that capture did not occur in this experiment. There was a main effect of display size such that participants were 41 ms slower when there were 9 items than when there were 5, $F(1,18) = 24.24$, $p < .001$. This is a 10 ms/item cost, which indicates that while search was not perfectly parallel, it was still quite efficient, which is typical for feature search trials. There was no interaction between distractor presence and number of items in the display, $F(2,36) = 1.83$, $p = .175$. Participants had consistent error rates across all conditions, so the results do not reflect a speed-accuracy tradeoff.

	Response Time (ms)		Error Rate (%)	
Color Singleton	5 Items	9 Items	5 Items	9 Items
Absent	721(83)	752(99)	4.3	3.9
Red	717(83)	761(100)	4.3	4.3
Green	719(81)	765(107)	4.2	4.3

Table 9. Mean reaction times and standard deviations in milliseconds, along with error rates for each condition.

Participants were able to resist attentional capture even when the color of the distractor could not be predicted on a trial-by-trial basis. The key difference between this experiment and the color-swapping condition of Experiment 5 is that here the two singleton colors were never the target color and any change in how participants responded to the singleton colors, in order to resist capture by those colors, could have remained throughout the experiment. This experiment demonstrates that participants can learn to resist capture by more than one color at a time.

General Discussion

The results of Experiment 5 show that capture can occur on feature search trials with heterogeneous displays under conditions that prevent the learning of an association between singleton status and a particular color or colors. When the trials had fixed color mapping (Experiment 5), that is, the majority of items were always one specific color and the color singleton was always another specific color, the typical lack of capture was obtained. In the color-swapping condition, where a trial could have either one of two majority colors and the singleton, if present, had the other of those colors, there was a significant amount of capture. In Experiments 6 and 7, participants were able to resist capture even when the majority color or singleton color had two possible values, as long as there was no overlap between the set of majority colors and the set of singleton colors.

This is in conflict with search mode theory, which predicts that attentional capture should either never occur on feature search trials, or at least not after participants have had time to fully get into feature search mode. These results also cannot be explained by the attentional window theory as originally put forth, since the physical stimuli on individual trials in the fixed and swapping conditions were essentially the same and should have affected the attentional window in the same way. If the attentional window in feature search mode is small enough to generally leave out the color singleton item, the effect of switching the majority/singleton color mapping should not be very different from switching only the majority color between two different colors, but clearly that is not the case.

It is also clear the previous trial has a strong influence on the current trial. It makes sense that importance would be placed on features of the previous trial's target that are truly predictive of the target, but it seems that some importance is placed on the previous trial's target color—the majority color--even though the target is not defined by its color and the target color on one trial is not predictive of target color on the next trial. On the current trial, attention is drawn even more strongly to a color singleton that has the previous trial's majority color than it would otherwise be, leading to increased attentional capture. If the colors had swapped and the previous singleton color had been inhibited this could make it slightly more difficult to attend to the target on the current trial, leading to increased attentional capture by the singleton. However, while capture was numerically higher on switch trials where the previous trial had contained a distractor, this effect was decidedly not significant.

The presence of capture on trials in the color-swapping condition where the previous trial had the same color mapping, for example a trial with green items and a red distractor preceded by a trial with green items, which is what was found, could be interpreted in one of two ways. There is a chance that the attentional capture effect resulted from observers being distracted by a color that had recently (several trials back) been the color of the target, and not because bottom-up capture is to be expected in the absence of learning. However, based on the findings of Vatterott and Vecera (2012), where capture was obtained until participants had sufficient experience with a specific color distractor, it seems unlikely that capture here resulted purely from the influence of attention drawn to the irrelevant color of the target several trials back in the sequence. We believe it resulted from participants being unable to associate the singleton distractor with a particular color, and that it takes longer than a single trial's worth of experience to form such an association.

The fact that participants do not experience capture when only the color singleton distractor color varies across trials and the majority color is constant suggests that whatever it is that allows observers to resist capture (de-weighting, inhibition, etc.) can occur for multiple colors simultaneously. There is some evidence that with a large number of possible singleton colors participants will not experience capture--neither by any of the colors they are familiar with nor by a novel color distractor, but that with fewer possible singleton colors only those colors that participants are experienced with can be resisted (Vatterott, personal communication).

The current results are compatible with either a feature weighting account or a dimensional weighting account. Under a feature weighting account (e.g. Wolfe, 2007) there is a master saliency map and top-down attention can only assign more or less weight to specific feature values (or a feature category, in the case of GS4). A dimensional weighting account could also explain the results (Müller, Remann, & Krummenacher, 2003), though only the version under which color categories are treated as separate dimensions rather than only being treated as values under the general dimension of color. Dimensional weighting is hierarchical, and posits that observers use top-down weightings to bias attention toward different feature dimensions, or in the case of color, sub-dimensions. Each dimension has its own saliency map. Whether an item with a certain feature value captures attention is determined both by whether it has the highest physical salience along its dimension and by the weighting given to that dimension. Under either account, in the fixed condition participants would be assigning more weight to the majority color while de-weighting the singleton color over time. In the swapping condition, participants might begin to adjust color weightings after every switch trial, but on average weight the two colors the same, leading to capture by which ever color had more physical salience on a given trial.

In the fixed majority/switching singleton experiment (Experiment 7) participants might add more weight to the majority color category while de-weighting both singleton color categories. It is likely that the maximum de-weighting of the two distractor colors took longer than for a single color, but in any case it was effective. In the switching majority/fixed singleton experiment

(Experiment 6), participants might have similarly added weight to both majority colors, while de-weighting the singleton color. It is also possible that most of the dimensional weighting only affected the features related to the target or to the color singleton.

Based on the evidence from various transfer studies as well as Vatterott and Vecera (2012) it is likely that the weighting mainly affects the singleton color, otherwise changing the singleton color would be expected to have less influence while changing the majority color would have more. This would make sense given that the presence of the majority color is not a very good predictor of whether the item is a target, since many non-targets share that color, while the singleton color is perfectly predictive of that item being a non target, therefore the singleton color is more informative.

Because we do expect that the amount of capture in the swapping condition would decrease to zero with enough same majority color trials in a row (since that is what one finds in fixed color versions), it makes sense to compare what is happening to priming of popout. A good follow-up experiment would be to carefully control the length of same and different runs while keeping the probability of a switch after any given trial the same. This would allow us to determine the number of trials that it takes for capture to decrease to zero. It would be much easier in this paradigm than in one similar to that used by Vatterott and Vecera (2012) since there is no issue with running out of distinct novel colors to introduce. This could allow a comparison with the cumulative effects of priming of popout.

Another interesting experiment would be to examine the effects of a varying target shape on feature search. In order to introduce target shape uncertainty, participants would have to know that the target could be one of two shapes, for instance circle or diamond. One or the other would appear on each trial with equal probability. Perhaps participants, having an attentional set that included both shapes, would be able to develop resistance to capture the same as participants in any feature search. However, it is possible that target uncertainty would interfere with this ability. It would also be possible to create a condition where there was target shape switching without uncertainty, where participants could be cued with the target identity before each trial, a verbal cue if experimenters wanted to avoid visual priming or a picture of a circle exactly how it would look in the search array if they wanted to induce visual priming.

Chapter 5: History and salience effects in singleton search

Experiment 8

One of the underlying motivations for the scientific study of distraction is that people are very interested in finding ways to reduce distraction in daily life, particularly in contexts such as school and work. The following study was partly motivated by the desire to find ways to reduce distraction in circumstances where it will ordinarily occur, specifically singleton detection search, in hope of gaining insight into how to reduce distraction from irrelevant items in real-word contexts, in particular for individuals with conditions such as ADHD.

On a theoretical level, there are also unexplained aspects of singleton detection vs. feature search. If it is the case that the occurrence of capture on singleton detection trials is due to a lack of learning on those trials, then it is left to explain exactly why learning does not occur during singleton detection trials with a consistent color singleton even though it will occur on feature search trials with a consistent singleton. Indeed, it remains to be seen whether past experience influences capture on singleton detection trials under any circumstance. It may be that during singleton detection trials, only bottom-up factors determine the magnitude of capture, although it seems unlikely.

One possibility is that the distractor is too salient when part of singleton detection displays and will always capture attention. However, prior exposure to a less-salient version of that feature (i.e. a less saturated color) might allow participants to become acclimated to the presence of that feature at levels where it will not always win the battle for salience, and learn that it is not pertinent (i.e. relevant to task goals). If the distractor were to increase in salience across trials, this learning might enable resistance to capture in the way that the training phase leads to resistance to capture where it would otherwise occur in transfer studies. We therefore wanted to look at history effects, both with a distractor of increasing salience and of decreasing salience. In the latter case, participants who experience a highly salient distractor at the beginning of the experiment might experience higher levels of capture than otherwise expected at all intensity levels as the salience of the distractor decreased over time. It may be hard to tell with certainty whether differences in capture magnitude for the two conditions at a given intensity are a result from a history of increasing salience, a history of decreasing salience, or the combined effects of both type of history effect, but the very existence of differences in the magnitude of capture and the same level of intensity in the two experiments would be illuminating. If these predictions hold, it might lead to practical implications for situations in which people want to reduce distraction by an item with known features.

In the following experiment there were three different conditions, tested in a between-groups design, all of which involved additional singleton trials modeled on the singleton detection trials in Leber and Egeth (2006b), meaning that there were three possible target shapes. In the increasing salience condition, color singletons appeared on half of all trials, starting as an undetectable reddish-gray for the initial trials and increasing to bright red as the experiment continued, as in Figure 16. In the decreasing salience conditions the color singletons began as bright red and dropped to indistinguishable levels. There was also a maximum salience condition where the color singleton was always bright red. The maximum salience condition was used to get an idea of the magnitude of capture expected over time with a salient singleton that was constant in intensity, and to see if the participants reached this magnitude of capture at lower levels of color intensity. Note that when I use 'intensity' I am referring to saturation, with low intensity being a desaturated red and the highest intensity being the highest saturation that could be achieved using the display.

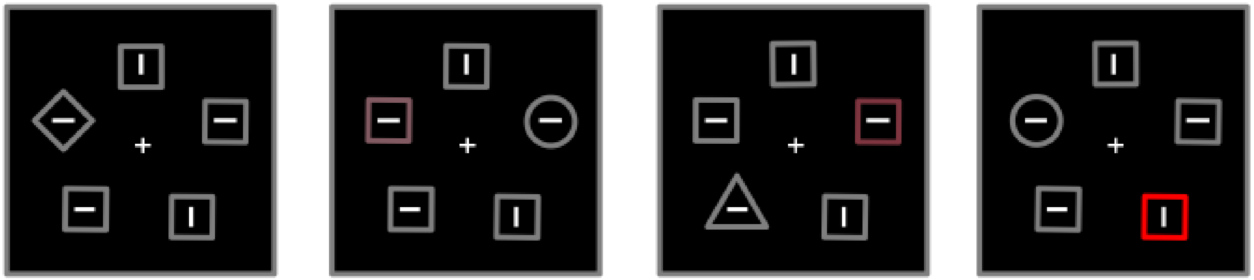

Figure 16. Displays with color singleton distractors of differing levels of salience, from imperceptible to maximum salience. In the actual experiment, the salience increased or decreased slowly across all trials and there were distractor absent trials throughout the experiment.

There are known history effects in the additional singleton paradigm, such as the influence of distractor prevalence (Müller, Geyer, Zehetleitner, & Krummenacher, 2009). The more practice observers had with a particular distracting singleton, the less interference it caused. In their Experiment 1, the prevalence of the distractor could either run up from 0% to 100% or run down from 100% to 0%. There was more distractor interference as distractor prevalence increased than as distractor prevalence decreased, both overall and at given levels of distractor prevalence. When comparing that study with the present one, keep in mind that their run-up condition was more comparable to the decreasing salience condition than the increasing condition. A less prevalent distractor is more pertinent than a highly prevalent one, due to expectancy effects, while a less intense distractor is less salient. Therefore, if intensity affects top-down attentional control somewhat similarly to prevalence, the results of the prevalence study would predict more capture in the decreasing condition than the increasing condition, in contrast to our hypothesis.

As for whether experience with the task can affect the magnitude of capture when there are no changes in the physical properties of the displays, with 1728 trials, Theeuwes (1992) did not find a reduction in attentional capture in the additional singleton paradigm when analyzing the trials divided into three sections. However, that experiment differed from the following in that the distractor present and absent trials occurred in alternating blocks instead of being intermixed, which affects the expectations an observer has about a given trial. In addition, the current experiment used three possible target shapes, rather than a consistent one, forcing participants into using a singleton detection strategy, whereas those in the Theeuwes study could have employed some degree of feature search.

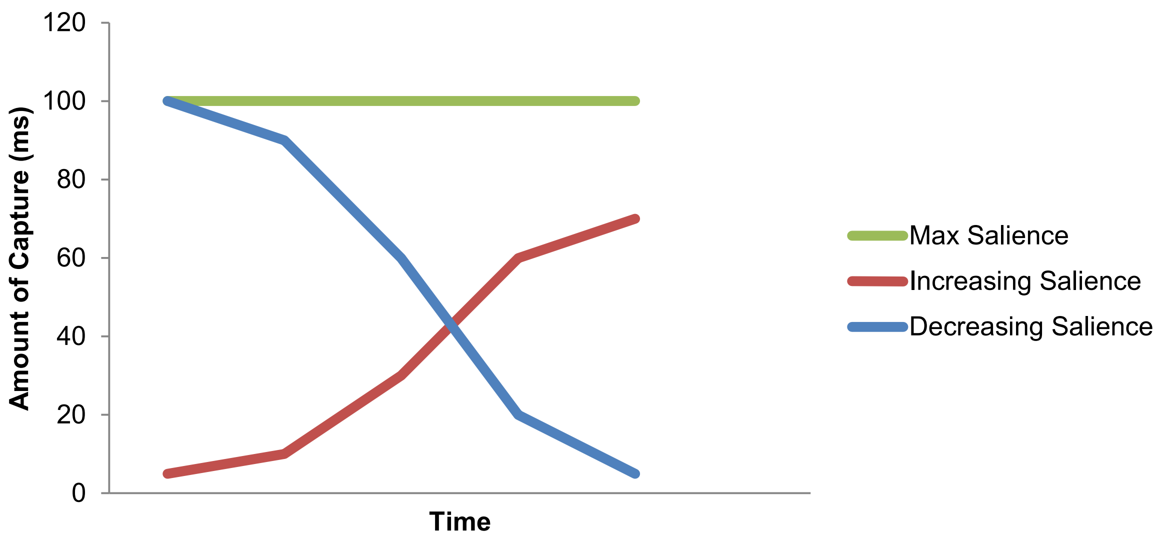

Figure 17. Predicted results. We expect a relatively constant and high magnitude of capture in the maximum salience condition, and a magnitude of capture that decreases to near zero in the decreasing salience condition. If it is true that gradually the increasing the salience of the irrelevant distractor allows resistance to capture to develop, we expect that the magnitude of capture in that condition would increase over time, but never reach the amount obtained in the decreasing and maximum conditions.

To understand our predicted results, it may help to refer to Figure 17. We expect based on the results of Theeuwes (1992) that in the maximum salience condition capture might be somewhat variable, but have no noticeable increasing or decreasing trend. We predict that the magnitude of capture in the increasing salience will not rise to that found in the maximum salience, and that participants will experience less attentional capture overall when the distractor increases in salience than when it decreases in salience, since in the decreasing condition capture would start and a high magnitude before decreasing. Of course, it would also be interesting if participants experienced more capture in the increasing salience condition than the decreasing condition. In addition, as long as the graphs of capture over time are not essentially mirror images of each other, regardless of whether there were overall difference in capture, we can reject the null hypothesis that only stimulus intensity affects attentional capture and conclude that history effects can impact capture.

Method

Participants

Participants were 30 (13 male) Johns Hopkins University undergraduates who participated in return for extra credit, and 10 were assigned to each condition. Participants had a mean age of 20.1 years and were all over the age of 18 with normal or corrected-to-normal vision. Participants were randomly assigned to one of the three conditions. Data from one participant in the decreasing salience condition was excluded from analysis because his accuracy was below 70%.

Apparatus

Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920x1080 resolution and a screen refresh rate of 60 Hz, which was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the ‘h’ keyboard key for horizontal or ‘v’ key for vertical.

Stimuli

The singleton displays were similar to those used by Leber and Egeth (2006b) except that the majority of items were gray rather than having a color value. Each display consisted of five or nine outline shapes arranged equally spaced around an imaginary circle 3º from the center of the display to the center of the shapes. Each shape contained a horizontal or vertical white line in the center. Each shape outline was .1º thick and the line inside was .5º in length and .05º in thickness. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. The non-target shapes were squares with sides measuring 1.3º. On each trial the target had an equal probability of being a circle (diameter 1.5º), diamond (sides 1.3º), or an upward pointing equilateral triangle (sides 1.5º). On singleton-absent trials, the outline shapes were gray in color (RGB: 128, 127, 127). The highest intensity color singleton was red (RGB: 255, 0, 0) and color singletons of intermediate intensity were all shades of reddish-gray. If a color singleton was present in the display, it was one of the non-targets.

Design

The target shape, target location, and orientation of the lines inside each one of the shapes were all randomly chosen on a trial-by-trial basis.

In the increasing salience condition, trials were divided into 128 levels of 10 trials each. Within each level, half the trials were randomly assigned to have 5 items and half 9. Half the trials were randomly assigned to be distractor absent and half color singleton distractor present. At the first level, the color singleton distractor had the same color value as the other items, meaning that technically there were no distractor-present trials, but for the purpose of analysis a random half of the trials were designated as distractor-present. After the first level, the RGB value of the color singleton increased by 1 for the red value and decreased by 1 for both green and blue. The last level had a color singleton distractor of maximum intensity red.

In the decreasing salience condition, the design was the same except that participants began with a level where the color singleton distractor was the maximum intensity red and the RGB value of the color singleton distractor decreased by 1 for the red value and increased by 1 for both green and blue after each level. The last level in this condition was technically a distractor-absent level, but was treated as if it contained color singletons for the purpose of analysis as in the increasing salience condition.

In the maximum salience condition, the design was like the other two conditions, except that when present the color singleton was always of the highest intensity red.

Procedure

Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the uniquely shaped item as quickly and accurately as possible. They were instructed that they would receive feedback for wrong answers and that distracting items might appear during the course of the experiment, and that they should try to ignore these items. They were *not* informed that the distracting item would be a color singleton. They were also shown four example displays so that they were exposed to all possible target shapes and both five and nine item displays. The example displays did not contain color singletons. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response or responded after 2,000 ms, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 1,280 trials long, which took most participants about 45 minutes. The instructions and procedure were the same for the three conditions, only the individual displays differed.

Results

The trials were divided into 16 bins of 80 trials each. Mean RTs were entered into a 3 (condition) x 2 (distractor) x16 (bin) mixed ANOVA. There was no main effect of condition, $F(2,26) = 0.16$, $p = .856$, which means that all groups had similar response times overall. There was a main effect of distractor, $F(1,26) = 269.76$, $p < .001$, such that participants were slower to respond when the color singleton distractor was present. There was a main effect of bin, $F(15,390) = 47.54$, $p < .001$, which appeared to be driven by a general decrease in response times over time.

There was no significant interaction between condition and distractor, $F(2,26) = 1.55$, $p = .231$, which means that the mean amount of capture (distractor present RT – distractor absent RT) was not significantly different between the three groups. Numerically, the greatest amount of capture occurred in the maximum salience condition, as seen in Figure 18.

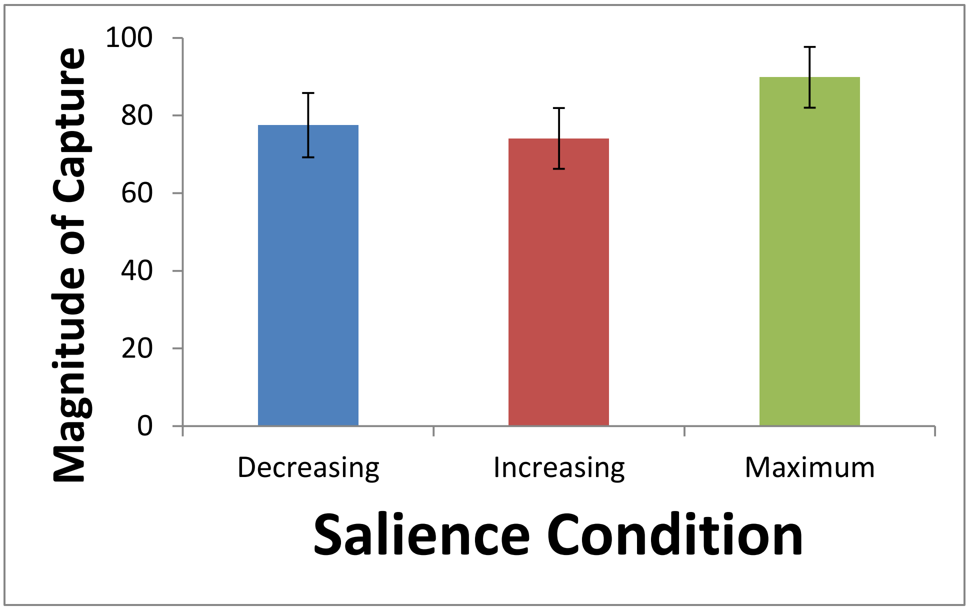

Figure 18. Mean magnitude of capture in the three different salience conditions. Error bars represent the standard error of the mean.

There was a significant interaction between condition and bin, $F(30,390) = 6.04$, $p < .001$, which means that the way the RTs changed over time differed between the three conditions, as seen in Figure 19 The key three-way interaction between condition, distractor, and time was also significant, $F(30,390) = 19.11$, $p < .001$. This means that the way the magnitude of capture changed over time differed between the three conditions, as seen in Figure [D].

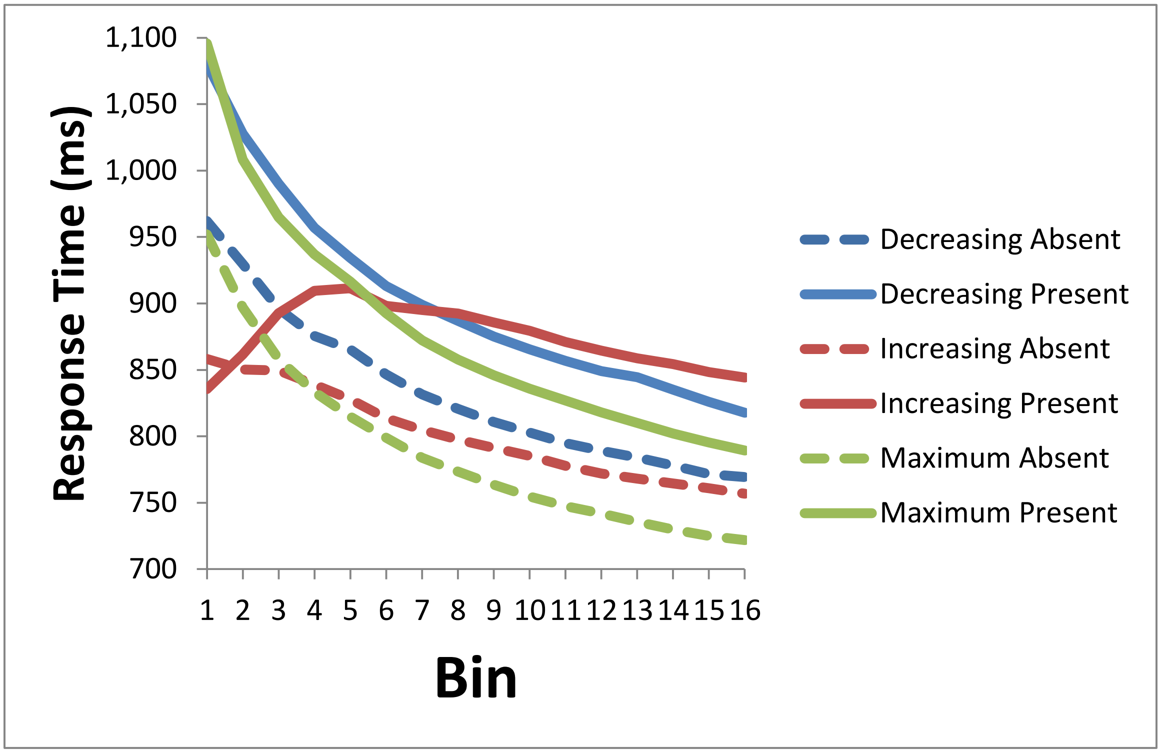

Figure 19. Mean RTs over time for both distractor absent and distractor present trials in the three different salience conditions. The trials were divided into 16 bins of 80 trials each.

Discussion

The lack of a significant difference between the mean magnitude of capture overall in the conditions was somewhat surprising. Not only was the magnitude of capture in the increasing condition not lower than that in the decreasing condition, the magnitude of capture was not any higher in the maximum salience conditions than the other conditions. The latter result strongly indicates that physical salience alone cannot explain these results. If only physical salience affected the magnitude of capture, the magnitude of capture should have been much greater in the maximum condition, where physical intensity was greater on average than in the other two conditions. Examining the data more closely, this appears to be due to a decrease in capture over time in the maximum salience condition. This demonstrates that top-down attentional control, not just physical salience, affects attentional capture even when participants are forced to use a singleton detection strategy.

Looking at Figure 19, it appears that the interaction between condition and bin was driven by the difference between the increasing salience condition and the two other conditions. In the increasing salience condition, response times on distractor present trials increased until the 5th bin of trials, which makes sense because the distractor was increasing in intensity. After that point, RTs decreased over time until they were close to the fastest level. RTs on the no-distractor trials in the decreasing salience condition decreased over time as in the other two conditions, but started out much faster. The curves from the maximum salience and decreasing salience conditions appear to be classic examples of the law of practice. Typically either a power function or an exponential function (see Heathcote, Brown, & Mewhort, 2000 for an argument for the exponential function rather than the more traditional power function) is fit to response time data to model the effects of practice.

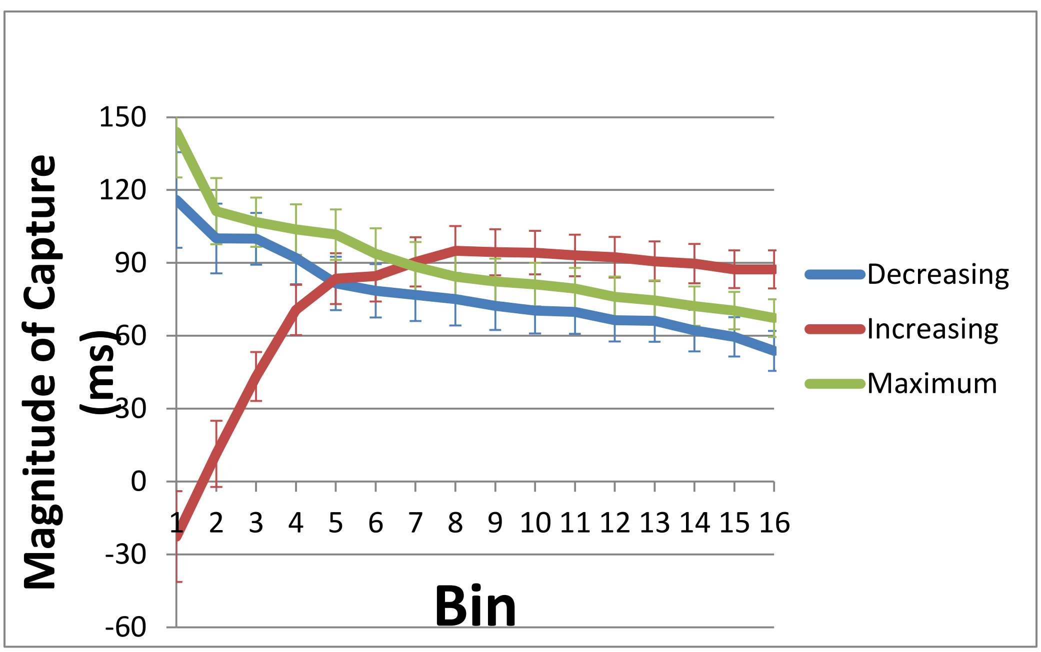

Figure 20. Mean magnitude of capture over time in the three different salience conditions. The trials were divided into 16 bins of 80 trials each. Error bars represent the standard error of the mean.

It is clear that when examined over time, as shown in Figure 20, the graphs of the increasing and decreasing condition were not mirror images, meaning that participants in the two groups did not experience the similar amounts of capture on trials of the same intensity. Therefore we can conclude that changes in stimulus intensity do lead to history effects in the additional singleton paradigm. Looking only at the magnitude of capture in the three conditions, we can see that although the interaction between condition and distractor was not significant, the magnitude of capture in the maximum salience condition was always slightly higher than that obtained in the decreasing salience condition. This makes sense given that in the decreasing salience condition even the first bin contained many trials where the color singleton had a slightly lower intensity than in the maximum salience condition (since there were 8 intensity levels in each bin). In the maximum salience condition, the magnitude of capture declined over time, despite the physical intensity of the red item remaining the same. This is likely due experience with the distractor, but may also result from the way RTs in general grew faster over time. In both the maximum salience and decreasing salience conditions, the amount of capture was initially quite high and then dropped sharply from bin 1 to bin 2, declining more gradually after that point. During the initial trials the high intensity salient singleton was probably quite surprising, especially given that participants were not specifically warned about the existence of a color singleton and were not shown any color singletons during the instructions or practice. This is probably the reason for the particularly high amount of capture on initial trials.

The magnitude of capture in the increasing salience condition started out near zero, which makes sense given that the color singleton did not exist for ten trials and only slowly reached a perceptible level. We can see clear evidence of capture by about the 3rd bin (since the first bin actually started out negative, which could only have been due to random variation, and the second bin only reached levels about that much higher than zero). Although the maximum RT on distractor present reaction times in the increasing salience condition peaked around the 5^{th} bin, the magnitude of capture in this condition peaked around the 8^{th} bin. After this point, capture appears to level off or even slightly decrease, as if experience with the color singleton was enough to counteract its increasing intensity. Capture never reached a magnitude as great as in the initial bins of the maximum salience and decreasing salience condition, possibly because there was nothing surprising about the presence of the color singleton as it reached higher levels of intensity. At the same time, after the magnitude of capture peaked in the increasing condition it never reduced to levels as low as in the maximum salience condition, despite the fact that participants in the increasing salience conditions did not experience the highest intensity distractor until the last ten trials of bin 16. This contradicts our initial hypothesis that slowly increasing the salience of the color singleton over time would make it easier to resist. Instead, if for a given high intensity color singleton trial one wants a participant to experience a reduced amount of attentional capture, one should allow that participant to experience as many trials as possible beforehand with color singletons of equal salience, as in the maximum salience condition.

The fact that RTs decreased over time, as participants gained more experience with the task, was not particularly surprising. The fact that the magnitude of attentional capture also decreased over time was somewhat less predictable. We do know that attentional capture fluctuates from trial to trial, and that the magnitude of capture on option trial can be predicted by pretrial activity in middle frontal gyrus (Leber, 2010), however these moment-to-moment fluctuations in attentional control do not explain the overall trend toward less capture. It would also have made sense if attentional capture eventually increased due to participants becoming fatigued and less able to focus attention, but this did not occur within the hour-long timespan of this experiment. A much longer experiment would be needed to see if the amount of capture in the maximum salience condition continued to trend downward or if it would level off to a stable amount. It would also take further analysis to determine whether attentional capture was occurring less frequently on later trials or whether participants became more efficient at reorienting.

What might explain the difference between Theeuwes's (1992) experiment where, with even more trials, there was no overall reduction in capture (although, there was a slight reduction in capture in the middle section of the experiment), and the current experiment, where there was a noticeable decline in the maximum and decreasing conditions? The most likely possibility is that in Theeuwes's experiment, the distractor absent and distractor present trials were divided into separate blocks. This would lead to very different history effects, given that participants would go from constant recent experience with a color singleton to periods of no recent effect of the color singleton. In that experiment, participants were also responding much faster overall, possibly due to the predictability of the target shape. There was no reduction in response times over time in Theeuwes's experiment as there was in the present study, which would make sense if RTs were at floor in that study, while RTs in the current study were not. The floor effects in response time might have resulted in a floor level of capture—if there is a floor level of capture by irrelevant singletons on singleton detection trials, which seems possible given that no study has found zero capture on additional singleton paradigm trials where participants are forced to use a singleton detection strategy. Finally, this experiment looked at smaller increments over time, so perhaps downward trends in RT and magnitude of capture were simply more obvious with this analysis.

Leber and Egeth (2006a) looked at capture over time on RSVP contingent capture option trials and found no reduction in capture, but there were only 320 trials in that case (preceded by 320 RSVP contingent capture singleton detection training trials). In addition, accuracy and not response time is the measure of capture in the RSVP contingent capture paradigm, so it is hard to draw a clear comparison between these results.

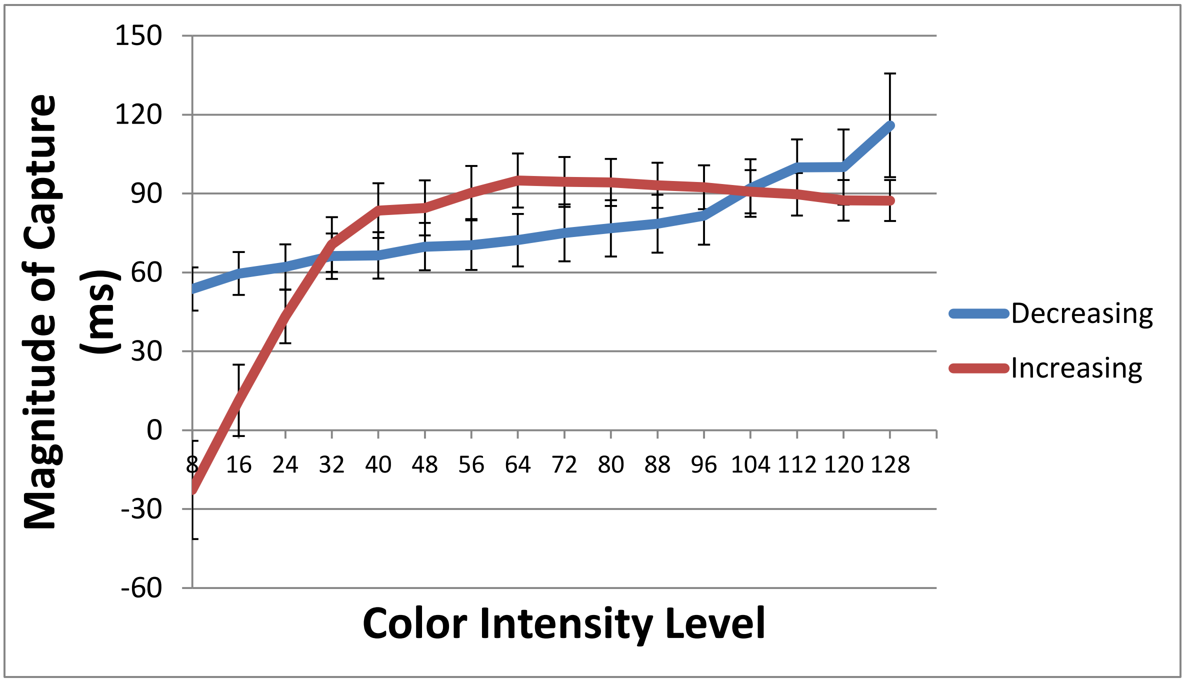

Figure 21. Mean magnitude of capture over time in the increasing and decreasing salience conditions plotted by color intensity level. The trials were divided into 16 bins. The labels on the x-axis correspond the highest level number included in that bin. Error bars represent the standard error of the mean.

In the decreasing salience condition the experiment must logically have ended with zero capture, since the color singleton faded away into nonexistence, but our analysis here was not fine-grained enough to capture that. What can be seen in Figure 20 is that the magnitude of capture on the last two bins in the decreasing salience condition was nowhere near as low as the essentially non-existent capture during the first two bins of the increasing salience condition. This is especially clear from looking at the two conditions plotted by color intensity level, as in Figure 21. It appears that for low-intensity color singletons, experience with a high-intensity color singleton led participants to be more susceptible to capture than participants who had no prior experience or prior experience with lower-intensity singletons. History effects in other visual tasks include children who perform worse at approximate number discrimination when given difficult problems first than when given easy problems first (Odic, Hock, & Halberda, 2014) so perhaps this effect is somehow related.

Even without a difference of overall amount of capture in the increasing and decreasing conditions, the effect of changing intensity bears some similarity to those of changing the prevalence (Müller et al., 2009), since in that study capture was different at the same level of prevalence depending on whether it was the run-up or run-down condition. Of course there are key differences in the two studies, since the distractors in that study were never physically different when present, as they were here. In addition, the target was always a circle, so there may have been differences in observers' search strategies, since they could have used a feature search strategy on some trials, unlike in the current study. The complete lack of capture found for higher prevalence distractors in the run-down condition could have been partly due to a shift in search strategy. In any case, both studies demonstrate that attentional control on a given trial depends on the type of past experience the observer has with the distractor.

A weakness of the current experiment was that we did not have the psychophysical function for the perceptibility of the color singleton. An important future addition to this work would be to run a psychophysical experiment to assess the detection threshold of the color singleton and possibly experiments to assess the just noticeable difference at key levels of stimulus intensity. In the current experiment it was not the case that the color singleton was increasing steadily in visibility in perceptual terms, and while the increasing and decreasing salience conditions were designed so that comparisons could be made without knowing the detection threshold, it would be helpful in providing more context for the results. After all, the detection threshold for the presence of a color singleton would presumably be less than the intensity necessary to produce attentional capture, since we know that color singletons don't capture attention if the color difference is less salient than the shape difference (Theeuwes, 1992).

Another possibility would be to run a condition with all of the intensity levels included in the increasing and decreasing conditions, but distributed at random, which would be a good condition to compare with the decreasing salience condition in order to tease apart the effect of decreasing salience and experience with the task. The maximum salience condition isn't as fair a comparison given that the intensity was on average lower in the decreasing salience condition, though it's remarkable how similar response times were in these conditions despite that fact. A random salience condition would have the same average salience as the decreasing condition, but without the history of experience with only more salient or equally salient distractors for any given trial, so we could see if beginning with maximally distracting trials really does lead to more distraction than having a random mix would.

One of the implications of our results is that reduction in capture over time can occur over time with the additional singleton paradigm even when the distractor salience does not change. Researchers should be aware of this when designing experiments where stimulus characteristics change over time. However, it is at least possible that this gradual reduction is absent or reduced when the salience of the color singleton is due to it being a color as opposed to gray, rather than being due to a difference in hue (since a red singleton among green distractors is commonly used). Ultimately, this is another example of the influence that past experience has on attentional orienting, even during parallel search for a singleton target. It is not clear whether attentional capture by an irrelevant singleton of sufficient salience can be ever be eliminated when participants are forced to use a singleton detection strategy, but the magnitude can certainly be changed by past experience. Bottom-up factors are not the only ones in play.

Chapter 6: Conclusions

The experiments in this thesis examined the way that experience with certain features affects the extent to which participants are distracted by irrelevant items while engaging in a search task. An observer performing a visual search must attend to the target in order to process it in a way that allows for a useful behavioral output. If a non-target item captures the observer's attention, the task will be more difficult. All of the current experiments employed variations of the additional singleton paradigm, where observers search for a target that is defined along a particular dimension (shape) and on some trials must do so in the presence of a salient distractor that is a singleton along an irrelevant dimension (color). The search could be for a shape singleton whose shape on a given trial was unpredictable (singleton detection trials), a shape singleton whose identity was known (option trials), or a non-singleton shape whose identity was known (feature search trials). Past experience with both target and distractor features was manipulated in various ways to see how that would affect attentional capture by the irrelevant color singleton distractor.

When all the experiments in this thesis are taken together, it appears that distraction by a color singleton can be minimized when observers have prior experience with a distractor of that same color, while prior experience with distractors of a different color will not aid in resisting capture. Bottom-up factors may initially lead to capture by salient stimuli, but with the right type of experience, observers can learn to resist that capture. Their top-down goal settings may be important in determining when resistance to capture will arise (only feature search), and the type of trials on which it can be employed (feature search and option). Following are the results that led to this conclusion.

The first two experiments employed the additional singleton transfer paradigm, where there is a training phase followed by a test phase. This is a between-subjects manipulation where participants receive different types of training, but an identical test phase. Here, participants received either feature search trials or singleton detection trials as the training and option trials at test. If there is a difference in attentional capture between the two groups at test, then something must have transferred from training to test. Past studies have shown that there can be transfer, such that participants who received feature search training do not experience attentional capture at test, while those who received singleton detection do (Leber & Egeth, 2006b). There are indications that whether transfer will occur is determined by the type of experience with distractors, rather than type of search, that participants get during feature search training, but so far this has been shown using cases where transfer does not occur (Zehetleitner, Goschy & Müller, 2012). The following experiments were designed to show that experience with the distractor's salient feature, its color, was sufficient for transfer to occur, while experience with the target features was not necessary.

Experiment 1, participants who received feature search trials training were able to continue to resist capture on option test trials, even though the shape of the target and non-targets were changed between training and test. This means that the singleton distractor also changed shape, but not color, from training to test. Participants who received singleton detection training experienced capture at test. Similar results were obtained in Experiment 2, where the shapes as well as the majority color (i.e. the color of the target and all non-targets except for the color singleton) were changed. In Experiment 3, capture occurred on option trials in the absence of training, which shows that capture should be expected by default on such trials (even with the use of a different shape set than is typical in similar studies). For that reason, a lack of capture on option trials after feature search training really should be thought of as resistance to capture, rather than capture being impossible or unusual during such trials. Together, these three experiments showed that experience with the defining feature of the target (shape) was not necessary for transfer effects to occur. Experience with the majority color (which was also the target color) and distractor shape (which was also the shape of the other non-targets) were also not necessary for transfer effects to occur. Transfer effects occurred as long as the singleton distractor color, the very thing that rendered the distractor distracting, remained the same.

Experiment 4 tested whether feature search training with a color singleton distractor could lead to resistance to capture on singleton detection trials, rather than on the option trials used in the first three experiments of the present work. This was to see whether the search strategy at test was important for the finding of transfer. If only experience with the singleton distractor color during feature search training mattered, and not type of search at test, one might expect transfer effects regardless of whether option trials or singleton detection trials were used. The training conditions here were all feature search, either with a distractor that was the same color at training and at test, with no distractor during training, or with a distractor that was of a different color during training than that which was used at test. In this experiment, a substantial capture effect was found at test, regardless of the type of training, which means that as of now there is no evidence that capture can be resisted during singleton detection search for an unpredictable target.

Experiments 5-7 were not transfer studies. Instead, they focused the feature search version of the additional singleton paradigm. In Experiment 5, half the participants received classic feature search trials where the majority and singleton color had fixed values for the whole experimental session. Half the participants experienced color-swapping feature search trials, where the majority color and singleton color could switch between trials. In the color-swapping condition, participants experienced capture, indicating that a lack of capture is not something that happens automatically on feature search trials. In Experiment 6, participants did not experience capture when they received feature search trials where the majority color could switch between two colors from trial to trial and the singleton was a completely different fixed color. In Experiment 7, participants did not experience capture when the majority color was fixed and the singleton could switch between two colors that were different from the majority color. Combined, these experiments show that the capture found in the color-swapping condition of Experiment 5 was not due to participants' uncertainty about the color of either the target or the distractor on a given trial. When participants cannot learn consistent color associations for the target and the distractor, they are unable to resist capture. They can resist capture even when more than one color is mapped to the target or distractor, as long as the target color can never be the distractor color and vice versa.

Experiment 8 focused on singleton detection trials, where participants searched for an unpredictable shape target and examined whether the magnitude of capture could be affected by history effects or only by the physical salience of the distractor. In the three between-subject conditions of this study, the majority color was gray and the singleton color was red. The singleton was either a maximum intensity bright red throughout the experiment, increased in intensity from reddish-gray to bright red, or decreased in intensity from bright red to reddish gray. The magnitude of capture decreased over time in the maximum salience condition, which was likely a practice effect. The magnitude of capture in the increasing and decreasing conditions was not the same for all given levels of distractor intensity, demonstrating that capture was influenced by the type of color singleton distractors that participants had previously experienced, not just by physical salience. Gradually decreasing the salience of the distractor appears to lead participants to be more prone to distraction by low-intensity singletons than they are in the increasing condition. Gradually increasing the salience of the distractor appears to lead to reduced capture with high-intensity singletons as compared to the decreasing condition. However, the lowest level of distractor interference from high-intensity singletons occurred when participants had substantial experience only with high-intensity distractors. Even during singleton detection trials where a salient color singleton reliably captures attention, the magnitude of attentional capture is affected by past experience.

Another way to consider the current experiments is to compare what happens during the three types of search that are possible with the additional singleton paradigm: singleton detection, feature search, and option trials where either a singleton detection or feature search strategy could be employed. When participants search for a shape singleton with an unpredictable identity, that is, when they are forced to engage in singleton detection, irrelevant, but salient, items will capture attention. This type of search includes the singleton detection training in Experiments 1 and 2, the singleton detection test phase of Experiment 4, and all conditions of Experiment 8. The color singleton distractor captured attention in all of these experiments (although in Experiment 8 the color singleton needed to be sufficiently salient), which is the typical finding for singleton detection trials.

When participants search for a non-singleton target with a predictable shape, which is a feature search, they also may or may not experience attentional capture depending on whether the experimental set-up allows for learning. In the mixed color condition of Experiment 5 where the target and distractor color could swap between trials, participants experienced capture, even though this was a feature search. In the fixed condition, where the target color and distractor color stayed the same throughout the experiment, participants were able to resist capture. They were also able to resist capture in Experiment 6 where the target could switch between colors, but the distractor had a separate color, and in Experiment 7 where the distractor could switch between the two colors, but the target was an entirely different color. This shows that, even during feature searches, participants must be able to learn to resist capture by a particular color (or colors) that is never associated with the target or else they will experience capture.

When participants search for a singleton target that is a predictable shape, so-called option trials, they experience capture following singleton detection trials, as in Experiments 1 and 2, and in the absence of experience as in Experiment 3. They are able to resist capture after feature search training where the distractor during training had the same color as the distractor during test), even after a change in target features (Experiments 1 and 2). Prior research has shown that feature search training with no distractor or a distractor of a different color does lead to participants resisting capture at test (Zehetleitner, Goschy & Müller, 2012). This demonstrates that in the additional singleton paradigm, resistance to capture not only results from experience with the salient feature of the distractor, but that experience with the features of the distractor is more important than experience with the features of the target.

Now that we have seen how learning from past experience can impact attentional capture in the additional singleton paradigm, we should consider these results in terms of the common theories of attentional capture. The first category includes the bottom-up theories of attention. These explain capture as being due to automatic, stimulus-driven processes. This category also includes the attentional window hypothesis. The second category is the top-down category, which includes search mode theory and contingent capture, which explain capture as being driven by participants' current goals. The third category includes explanations that allow for the contribution of various types of selection history. These differing sources of attentional control are not necessarily mutually exclusive, but bottom-up and top-down theories have historically been presented in opposition to each other. The preceding results demonstrate the importance of incorporating selection history into theories of attentional control.

The current work demonstrates that attentional guidance is not only determined by bottom-up factors. Even for physically identical displays, there are circumstances where participants will either experience capture by a physically salient item or resist capture, depending on how past experience is manipulated. This can be seen in comparing the capture results obtained on option trials in Experiments 1-3, where singleton detection training or no training resulted in capture on option trials and feature search training resulted in resistance to capture. It can also be seen by comparing the results from feature searches in Experiments 5, where individual trials in the color-swapping condition were identical to those in the fixed color condition but capture only occurred in the color-swapping condition. This is evidence against a completely bottom-up account of capture.

In Theeuwes's (2004) explanation of attentional capture, there is an element of top-down control, but only of the attentional window size. Under this view, only items inside the attentional window are processed in a way that allows them to potentially guide attention. If the current findings are explained by past experience with particular features, there is no need to invoke the attentional window to explain these results. Indeed, it is hard to see how narrowing or expanding the attentional window could explain the different circumstances under which capture does and does not occur. The specific feature values should not affect this, only the type of search and the amount of heterogeneity in the display. Narrowing of the attentional window and a slowing of search rate should affect the processing of salient distractors in the same way, whatever their specific color.

At the same time, the current work shows that in the absence of the right type of prior experience, bottom-up factors can be more important that either search mode theory or contingent capture would predict. Under conditions where learning about specific features is impossible, as in the condition of Experiment 5 where target and distractor color could swap places, the irrelevant singleton did capture attention. Attentional guidance to the most physically salient item does appear to be the default on option trials and in the absence of consistent experience with the potentially distracting feature, but current results do not speak to whether this is entirely due to bottom-up guidance or a top-down setting for detecting singletons.

Some of the current findings present a challenge to search mode theory in its current form, particularly Experiment 5. Search mode theory predicts that participants who have experience with a particular search mode will continue to use that search mode on similar tasks for as long as it is a viable strategy. It also predicts that whenever participants are forced to use a feature search strategy, they will not be distracted by irrelevant singletons. However, in Experiment 5, participants who were given classic feature search trials experienced capture when target and distractor colors switched. It appears that resistance to capture arises due to experience with a stimulus, not automatically as a function of employing a feature search strategy.

Despite these findings, the emphasis that search strategy is given in search mode theory does appear justified. Resistance to capture only arises during feature search trials, not option trials, as seen in Experiment 3. And, as seen in Experiment 4, there is no evidence that resistance to capture can transfer to trials where a singleton detection strategy is mandatory. Unfortunately, there is currently no way to demonstrate the extent to which participants are using a particular search strategy on option trials and whether that, separate from previously acquired resistance to capture by a specific feature, influences resistance to capture. Participants do not have good insight into their own strategies and it is clear that capture can occur even when a feature search strategy is employed.

These results all come from the additional singleton paradigm, where any distractor interference is coming from an irrelevant dimension. It would be interesting to see which of these results can be replicated with either the spatial cuing or RSVP contingent capture paradigms. After all, these are all attentional capture paradigms and in all of them similar effects of differing selectivity depending on the type of target have been found. That is, there are versions of all three paradigms where the target is a singleton and either all singletons or all singletons along a particular dimension, capture attention. There are also versions where a non-singleton target is defined by a particular feature value and only items that possess that feature value capture attention.

On the other hand, it would seem plausible for the mechanisms underlying capture in all three paradigms to be essentially the same. On the other hand, it would be a mistake to assume that results from the additional singleton paradigm will generalize to contingent capture paradigms, especially given that there is no correlation between individual differences in susceptibility to attentional capture in the additional singleton paradigm and RSVP contingent capture paradigm, which could indicate a critical difference in the mechanisms underlying the two (Kawahara & Kihara, 2010).

The contingent capture literature focuses on the similarity between the target and distractor (since capture distractor is assumed to be contingent on its similarity to the target), rather than experience with the target per se. Based on the research that has been done, we do know that experience has an effect on attentional control in contingent capture paradigms (Leber & Egeth, 2006a). However, resistance to capture in those studies seems to be less strongly tied to a particular feature. That is, in at least one contingent capture transfer study (Leber, Kawahara, & Gabari, 2009), participants were able to resist capture by distractors with a specific feature they had not yet experienced, which has yet to be shown with additional singleton paradigm. In the contingent capture paradigm, learning to resist a particular feature may not play a key role, although it might be part of the story

Therefore, it is possible that for contingent capture paradigms, the attentional set may be more crucial for explaining when capture will or will not take place. Further research is needed, although it must be carefully designed since contingent capture paradigms do not usually use distractors that have a salient feature along a totally different dimension than the dimension that defines the target. This will make it hard to make some of the manipulations used in the present research. For instance, it would be ideal to be able to do a contingent capture manipulation involving feature search where the target and distractor swap some feature, as in Experiment 5. The problem is that this would not work for a color distractor and color-defined target, as are typically used during contingent capture feature search, since if color defines the target, the target color cannot be changed within the experiment without causing complications.

The theories that best explain the current results are likely those that involve the weighting of sensory signals. In cases where attentional capture was successfully resisted, participants would have had to set the weight of the distractor color to 0, or very close to zero, in order to eliminate guidance from its strong bottom-up signal. The evidence here indicates that specific colors (e.g. precise shade of red), or color categories (e.g. red), or possibly relative color (e.g. more red), are what is being weighted or de-weighted, rather than different feature dimensions, since otherwise participants would presumably have been unaffected by the color swapping in Experiment 5, since having the majority and singleton colors switch should not have mattered if all color information had been de-weighted, although this is debatable. For instance, the current version of dimensional weighting appears to treat color categories as different dimensions (see Zehetleitner et al., 2012). These weights do not seem to be explicit or under voluntary control, or else participants on option trials would presumably adjust their weights in order to resist capture, but attentional guidance does seem to be controlled in a way that is somewhat flexible and not only due to sensory signals.

Now that we have considered how the present results relate to theories of attentional capture, we will return to the more general theories of attention discussed in Chapter 1. These were feature-integration theory, theory of visual attention/neural theory of visual attention, biased competition, and Guided Search 4.0. The results from the current additional singleton studies do not make a strong case for adopting one theory and rejecting the others, but the different theories do have different levels of explanatory power.

Feature-integration theory does not include attentional weighting, so is not the best theory for explaining either attentional capture or resistance to capture. However, the question of whether the target shape in feature searches can be found through parallel processing or not remains an important question to consider. This is also the theory that involves the focus of attention moving from location to location, so may be important to other studies where a spatially-based explanation for the magnitude of capture is given, although the current work does not rely on such a process.

The theory of visual attention (Bundesen, 1990) involves placing higher weights on the sensory signals from pertinent items. It makes an attempt to model how target stimuli might gain attentional weight over time, while distractors decrease in attentional weight. It predicts that improvement will only occur when the target is consistent, as in feature search and option trials. Practice effects are presumed to be absent when the targets can sometimes become the distractors, which might explain the case where practice effects were absent when the color of the target and distractor could swap. TVA provides a good underlying explanation for the current results because it explicitly takes experience with distractors into account.

Biased competition is similar to TVA, but it places emphasis on the attentional template. The results from Experiment 1 and 2 of this thesis suggest that the attentional template for the target is not actually key to attentional guidance, since capture can be resisted even when target features change. To fully explain current results, the biased-competition model might need to include some type of negative attentional template that lead toward a bias that disfavors distractor features.

Guided Search 4.0 has some problems when explaining resistance to capture by highly salient singletons because the current model does not allow the weighing of the bottom-up signal to go to zero, although if it goes close enough to zero that salience from being a color singleton is no longer enough to override the guidance that comes from weighting a certain channel, perhaps that does not matter. More problematic is the fact that to explain the current results there needs to be a mechanism for lessening the weight given to specific features rather than all bottom-up input. This mechanism also needs to allow that lack of weight to persist even when guiding features change, as in Experiments 1 and 2.

In sum, the current work has shown that past experience and learning must be incorporated into theories of attentional guidance and of attention as a whole. When searching for a shape target in the additional singleton paradigm, participants are differentially affected by a color singleton distractor depending on the context of the entire experiment, and not just the physical features of that particular trial. During the search for a predictable target, participants can learn to resist capture by a color singleton as long as the distractor color can be consistently mapped to the distractor. During the search for an unpredictable singleton, the magnitude of capture can be affected by past history. In order to experience reduced by distraction by a salient singleton that is irrelevant to task goals, observers need experience with the distracting feature of that singleton.

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